High Precision Form Crush Profiling of Diamond Grinding Wheels
High Precision Form Crush Profiling of Diamond Grinding Wheels

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. dr. ir. J. T. Fokkema,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen

op woensdag 12 november 2008 om 12.30 uur

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Energieonderzoek Centrum Nederland

ISBN 978-90-9023412-0

Dit onderzoek is mede gefinancierd door SenterNovem een agentschap van het Ministerie van Economische Zaken in het kader van het Innovatiegericht Onderzoeksprogramma (IOP) Precisietechnologie.
First of all I would like to thank my promoter Prof. B. Karpuschewski former head of the Precision Manufacturing and Assembly (PMA) group at the Delft University of Technology and now connected to the Otto-von-Guericke University in Magdeburg. I would especially like to thank my co-promotor André Hoogstrate, not only for his remarks and guidance but also for the discussions we had, often about production technology but also often off-topic.

This work has been carried out as part of a cooperative project with the Energy research Centre of the Netherlands (ECN) within the frame of the Innovation-oriented Research Programme (IOP) Precision Technology. From ECN I would like to thank in the first place Jaco Saurwalt for his valuable advice, discussion and encouragement. I would like to thank Guido de Jong for his part in the design of the set-up, Bas Wardenaar for his support during the manufacturing of the device and Erik Schuring for his support with the microscopy and material analysis.

During the last 5 years I have had the chance to work with many people from different companies and backgrounds. I would like to thank everybody for their interest, encouragement and openness to share information. This has been very valuable to assure the practical relevance of this work. I am especially grateful to the companies represented in the steering committee of the IOP project for their interest and cooperation.

I would like to thank Jan Savenije for his help with the initial design of the hydrostatic bearings.

A special word of thanks should go to the people at the Technology Centre for abrasives engineering of Saint-Gobain Diamantwerke in Norderstedt for their hospitality and support during the months that I stayed there and afterwards. I would like to mention Thomas Ardelt and Jörg Rucker by name for making this worthwhile period possible.

I would like to express my gratitude to all colleagues at the TU Delft not only for their professional help, but even more for their friendship. Some of them I would like to mention by name. First of all the laboratory staff that helped me to get everything running: George Schrumpf, Wout van Sorge and Jos van Driel. But foremost Harry Jansen: we spend numerous hours together keeping the machine running; I highly appreciate your dedication and friendship. A special word of thanks should go to my fellow PhD researchers: Tolga Susuzlu, Rogier Blom, Vincent Henneken, Viktoria Bana, Vu Ngoc Pi, Marcel Achtsnick, Iwan Kurniawan, Defeng Lang and Peiyuan Li. We are all in the
same situation, experiencing the same difficulty and loneliness that belongs to writing a PhD thesis.
Thank you for all the lunches and coffee breaks, for the good ideas and help and most of all for your friendship.
For his help with preparing this manuscript and the cover for printing I like to thank my friend Ubbo Noordhof.
I would like to express my gratitude to my parents and grandparents who have always let me make my own choices and allow me my mistakes. My father and grandfather fuelled my interest in technology when I was young and this is still the driving factor in my professional life.
And finally I would like to thank you Babette for your love, encouragement and support. I realize the last year has been tough for both of us and I could not have achieved this without you.

Västerås, August 2008

Jeroen Derkx
Summary

High precision form crush profiling of diamond grinding wheels

Grinding is a since long known manufacturing process that is able to cut hard materials. It makes use of circular bonded abrasive tools that are rotated at high speed and brought into contact with the workpiece to remove material. Nowadays the hardest of materials used in engineering like hardened steels, tungsten carbide based hardmetals and ceramics can be ground with the super-abrasives cubic boron nitride and diamond. The use of diamond as an abrasive, having the highest hardness known, opened many new applications in grinding and rationalized existing ones. However it brought also challenges of its own. One of the most profound challenges is found in the area of conditioning of diamond grinding wheels. Conditioning is the preparation of the grinding wheel needed to make it ready for use. As grinding wheels wear inevitably, conditioning has to be repeated at certain intervals during the lifetime of the grinding wheel. Conditioning consists of 1) truing and profiling, that is, to make the grinding wheel run true and remove run-out and to give it the required profile, 2) sharpening, that is creating space between the abrasive grains by removing binder material and 3) cleaning, that is removing the debris from grinding to make sure that the grinding wheel surface does not get clogged.

Conventional grinding wheels are made of abrasives that were much less hard than diamond (e.g. aluminum oxide and silicon carbide) diamond is used in conditioning tools to profile these wheels. With the arrival of diamond as an abrasive in the grinding wheel, profiling of these wheels has become a challenge in itself. Several approaches where developed, some tried to use a non mechanical (e.g. thermal or chemical) principal to profile the wheel, other tried to make the wear manageable. The achievable accuracy with these methods is however limited.

In this work a profiling method has been used that can principally achieve high accuracies and is still a mechanical method making integration on a grinding machine straightforward. This method is called crushing and relies on a rotating profiling tool, having the same circumferential speed as the grinding wheel, which is pressed into the grinding wheel. In this way only normal forces are exerted on the diamond grains in the wheel. Provided that the grinding wheel has a brittle bond system, the bond will fracture and the grains can drop out of the bond. In this way the wear of the profiling tool is limited.
The crush method is used with a so-called form roll. This form roll has a small contact area with the grinding wheel and the demanded profile is created by traversing the form roll along the contour of the grinding wheel. This makes this method flexible in creating various profiles. The current systems available for this process limited the process performance. Therefore a complete new profiling device is developed in this research. The main features of this device include:

- Hydrostatic bearing of the form roll spindle for high running accuracy, damping and stiffness.
- An extra swiveling axis to tilt the form roll +/- 70 degrees.
- A servo controlled form roll drive system.
- An integrated acoustic emission (AE) contact detection system.

Based on this set-up the prerequisite for crushing: the synchronization of the form roll and grinding wheel speed was studied. A new control method, guaranteeing optimal synchronization, was developed based on an alternating torque and speed control and the AE signal. It was shown that this system leads to the synchronized speed, even if, for some reason, the initial speed is incorrect.

As crushing is still a mechanical method, form roll wear is unavoidable. Different materials for the form roll were tested for their wear behavior in crushing. Form rolls reinforced with chemical vapor deposited (CVD) diamonds outperformed all other materials by far. Among the non-diamond materials hardened steel gave the best results.

Currently in industry these CVD diamond rolls are used. The rolls are sent back to the manufacturer for regrinding when worn. In this project the need to regrind the form rolls on the machine was recognized as this 1) increases the flexibility of the end-user to adapt the form roll top radius and the regrinding interval to the profiling task at hand, 2) increases the accuracy of the form roll as clamping errors are avoided and 3) reduces the operational cost of the profiling system. The added swivel axis on the profiling device made regrinding on the machine possible. Regrinding of the industry standard diamond reinforced form rolls proved to be both technically feasible and economically viable.

The flexibility of the process is extended also by the fact that the swivel axis removes the limitation in achievable profile details imposed by the top angle of the form roll.

To investigate the application area of form crushing a set of grinding wheels with different properties was used and compared. It was shown that vitrified as well as a bronze bonded grinding wheel can be crushed and that the damage to the grinding wheel layer induced by the crushing process is not more than several micrometer. Furthermore very fine-grained grinding wheels could be profiled, these wheels showed to be difficult to crush in earlier researches. Although the different properties of the wheels led to varying results in the forces, roll and wheel wear etc. it was shown that the range of profilable wheels is considerable, making it possible for the end-user to adopt the grinding wheel to the application.
Three different case studies were performed showing the potential and limitations of the form crush profiling process. Overall, the developed system is capable of flexible, high-accuracy profiling of diamond grinding wheels. Furthermore, the method is a step toward the ultimate goal of fully automated flexible profile grinding.

Jeroen Derkx
Samenvatting

Hoognauwkeurig vorm crusheren van diamantslijpschijven

Slijpen als bewerkingsproces heeft een lange geschiedenis en is geschikt voor het bewerken van harde materialen. Het maakt gebruik van cirkelvormige gereedschappen gemaakt van bij elkaar gebonden abrasief. Door deze gereedschappen met hoge snelheid rond te draaien en in contact te brengen met het werkstuk kan materiaal worden afgenomen. Tegenwoordig kunnen zelfs extreem harde materialen zoals gehard staal, wolframcarbiden en keramieken worden geslepen door gebruik te maken van de super-abrasieven kubisch boriumnitride en diamant. Het gebruik van diamant, dat de hoogste hardheid heeft van alle bekende materialen, als abrasief heeft geleid tot vele nieuwe toepassingen van slijpen en heeft bestaande processen gerationaliseerd. Het gebruik van diamant bracht echter ook nieuwe uitdagingen met zich mee. Een van de grootste uitdagingen wordt gevonden in het conditioneren van diamanten slijpschijven. Conditioneren van een slijpschijf betreft de voorbereidingen die nodig zijn voordat een slijpschijf gereed is om te slijpen. Aangezien slijpschijven tijdens gebruik onvermijdelijk slijten is het conditioneren een terugkerende bezigheid tijdens de levensduur van de slijpschijf. Conditioneren bestaat uit: 1) profileren, waarbij ervoor gezorgd wordt dat de schijf exact rond loopt en het juiste profiel wordt aangebracht, 2) scherpen, waarbij er spaanruimte tussen de korrels wordt gecreëerd door bindingsmateriaal te verwijderen en 3) reinigen, waarbij vervuiling die op de schijf achterblijft tijdens gebruik, wordt verwijderd zodat het oppervlak niet dicht gaat zitten.

Conventionele slijpschijven worden gemaakt van abrasieven die duidelijk minder hard zijn dan diamant (bijvoorbeeld aluminiumoxide en siliconcarbide). Diamant wordt dan gebruikt in de gereedschappen om deze slijpschijven mee te profileren. Met de komst van diamant als abrasief in de slijpschijf is het profileren van deze slijpschijven een uitdaging op zich geworden. Verschillende methodes zijn ontwikkeld, sommige maken gebruik van een niet-mechanisch proces (bijv. thermisch of chemisch) om de schijf te bewerken. Andere methodes proberen de invloed van de hoge slijtage aan het profilerengereedschap te beperken. De nauwkeurigheid van deze methodes is echter beperkt.

In dit onderzoek is gebruik gemaakt van een profileremethode waarmee in principe een hoge nauwkeurigheid kan worden gehaald maar die gebaseerd is op een mechanisch proces wat de implementatie op een slijpmachine vereenvoudigd. Deze profileremethode staat bekend onder de
naam cruiseren. Er wordt gebruik gemaakt van een roterend profileergereedschap dat dezelfde
treksnelheid heeft als de slijpschijf. Dit gereedschap wordt in de slijpschijf gedrukt waardoor er
alleen een normaalkracht optreedt in het contactvlak. Op de diamantkorrels wordt een
normaalkracht uitgeoefend, hierdoor kunnen de bindingsbruggen die de korrel in de schijf
vasthouden breken waardoor de korrel in zijn geheel uit de slijpschijf valt. Voorwaarde voor deze
methode is dat het bindingsmateriaal bros is. Door het ontbreken van slip tussen de slijpschijf en
het profileergereedschap wordt de slijtage aan het gereedschap verminderd.

De cruisermethode is gecombineerd met een zogenoemde vormrol. Deze vormrol heeft een klein
contactvlak met de slijpschijf en het gewenste profiel wordt gecreëerd door de vormrol langs de
contour van de slijpschijf te bewegen. Hierdoor is de methode flexibel in het creëren van
verschillende profielen. De systemen die tot nu toe beschikbaar waren voor dit proces waren niet
optimaal waardoor niet het maximale resultaat bereikt werd. Om deze reden is er in dit onderzoek
een volledig nieuw profileerapparaat ontwikkeld. De belangrijkste eigenschappen van dit apparaat
zijn:

- Hydrostatische lagering van de vormrol spil voor een hoge rondlopnauwkeurigheid, demping en
  stijfheid.
- Een extra zwenkas waarmee de vormrol +/- 70 graden kan worden gekanteld.
- Een servo-geregelde aandrijving voor de vormrol.
- Een geïntegreerd akoestische emissie (AE) contact detectie systeem

Met deze opstelling is de eerste vereiste voor cruiseren: de synchronisatie van de omtreksnelheden
van de vormrol en de slijpschijf, onderzocht. Een nieuwe regelmethode, gebaseerd op een
alternerende koppel- en snelheidsregeling en gebruik makend van het AE signaal, is ontwikkeld. Dit
systeem bereikt automatisch de optimale snelheid, zelfs wanneer er gestart wordt met een volledig
verkeerde startsnellheid.

Omdat cruiseren nog steeds een mechanische methode is, is slijtage aan de vormrol
onvermijdelijk. Daarom zijn verschillende materialen voor de vormrol onderzocht op hun slijtage
eigenschappen tijdens cruiseren. De vormrollen die versterkt waren met ‘chemical vapour
deposited’ (CVD) diamant presteerden vele malen beter dan de andere materialen. Van de andere
materialen gaf gehard staal de beste resultaten.

Het gebruik van deze CVD diamanten vormrollen is gebruikelijk in de industrie. Wanneer deze rollen
gesleten zijn, worden ze terug gestuurd naar de fabrikant die ze dan weer in vorm kan brengen. In
dit project is de noodzaak om de vormrollen op de machine na te slijpen onderkend omdat dit 1) de
flexibiliteit van de eindgebruiker verhoogt aangezien deze de vormrol toradius en het
herslijpinterval aan kan passen op de situatie, 2) de nauwkeurigheid van de vormrol verhoogt
doordat er niet meer omgespannen hoef te worden, en 3) de operationele kosten van de methode
beperkt. De zwenkas van het profileerapparaat maakte het naslijpen van de vormrollen op de
machine mogelijk. Het naslijpen van deze diamanten rollen bleek zowel technisch mogelijk als economisch haalbaar.

De zwenkas heeft als tweede voordeel dat het de beperkingen aan de maakbare contouren opheft die normaal gesteld werden door de topkant van de vormrol.

Om het toepassingsgebied van vormcrusheren te onderzoeken is een set slijpschijven met verschillende eigenschappen geprofileerd en vergeleken. Hieruit is gebleken dat zowel keramisch gebonden als brosse brons gebonden slijpschijven crusheerbaar zijn en dat de beschadiging van de slijpschijf door het crusheerproces niet meer is dan enkele micrometers. Ook bleek het mogelijk om zeer fijncorrelige slijpschijven te crusheeren, iets wat in eerdere onderzoeken niet was gelukt. De verschillende eigenschappen van de slijpschijven resulteerden in verschillende krachten en slijtages aan de rol en de schijf. Dit gaf ook aan dat er een grote variatie aan slijpschijven is die gecrusheerd kunnen worden wat de eindgebruiker de mogelijkheid biedt om de slijpschijf af te stemmen op de toepassing.

Drie verschillende praktijkvoorbeelden zijn uitgewerkt om het potentieel en de beperkingen van het vorm crusheer proces te illustreren. Het ontwikkelde systeem is in staat om diamanten slijpschijven op flexibele wijze te profileren met hoge nauwkeurigheid. Dit systeem is daarmee een stap in de richting van volledig geautomatiseerd flexibel profiel slijpen.

Jeroen Derkx
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<th>Unit</th>
<th>Description</th>
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<tr>
<td>$A_{ax}$</td>
<td>[m$^2$]</td>
<td>Effective area of the axial bearing</td>
</tr>
<tr>
<td>$a_e$</td>
<td>[m]</td>
<td>Depth of cut in grinding</td>
</tr>
<tr>
<td>$a_{re}$</td>
<td>[m]</td>
<td>Radial feed grinding wheel in regrinding</td>
</tr>
<tr>
<td>$a_{ed}$</td>
<td>[m]</td>
<td>Depth of cut in dressing</td>
</tr>
<tr>
<td>$a_{ed,cum}$</td>
<td>[m]</td>
<td>Cumulative depth of cut in dressing</td>
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<tr>
<td>$a_{ed,tot}$</td>
<td>[m]</td>
<td>Total depth of cut in dressing</td>
</tr>
<tr>
<td>$b_d$</td>
<td>[mm]</td>
<td>Width of dressing tool</td>
</tr>
<tr>
<td>$b_i$</td>
<td>[mm]</td>
<td>Width of grinding wheel</td>
</tr>
<tr>
<td>$C_{ax,0}$</td>
<td>[N/m]</td>
<td>Design stiffness of the axial bearing</td>
</tr>
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<td>$C_{mach}$</td>
<td>[N/m]</td>
<td>Stiffness of the grinding machine</td>
</tr>
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<td>$C_{prof}$</td>
<td>[N/m]</td>
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</tr>
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<td>$C_{rad}$</td>
<td>[N/m]</td>
<td>Radial stiffness of form roll radial bearing</td>
</tr>
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<td>$C_{struct}$</td>
<td>[N/m]</td>
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<tr>
<td>$C_{tot}$</td>
<td>[N/m]</td>
<td>Total stiffness of the profiling system</td>
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<tr>
<td>$D_2$</td>
<td>[-]</td>
<td>Design criterion for stability of hydrostatic bearing</td>
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<tr>
<td>$d_{eq}$</td>
<td>[m]</td>
<td>Equivalent diameter</td>
</tr>
<tr>
<td>$d_{geo}$</td>
<td>[m]</td>
<td>Geometrical constant used in calculation of contact width on profiles</td>
</tr>
<tr>
<td>$d_r$</td>
<td>[m]</td>
<td>Form roll diameter</td>
</tr>
<tr>
<td>$d_{r,0}$</td>
<td>[m]</td>
<td>Initial form roll diameter</td>
</tr>
<tr>
<td>Symbol</td>
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<td>Description</td>
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<td>------</td>
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<tr>
<td>( \text{d}_{\text{rad}} )</td>
<td>[m]</td>
<td>Diameter of radial bearing</td>
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<td>[m]</td>
<td>Grinding wheel diameter</td>
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<tr>
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<td>[m]</td>
<td>Initial grinding wheel diameter</td>
</tr>
<tr>
<td>( \text{e} )</td>
<td>[m]</td>
<td>Displacement of eccentricity</td>
</tr>
<tr>
<td>( F )</td>
<td>[N]</td>
<td>Force</td>
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<tr>
<td>( F'_{\text{nd}} )</td>
<td>[N/m]</td>
<td>Specific normal force in dressing</td>
</tr>
<tr>
<td>( F'_{\text{nd,crushing}} )</td>
<td>[N/m]</td>
<td>Specific normal crushing force caused by material removal</td>
</tr>
<tr>
<td>( F'_{\text{nd,roll}} )</td>
<td>[N/m]</td>
<td>Specific normal crushing force caused by rolling contact</td>
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<td>[N/m]</td>
<td>Specific tangential force in grinding</td>
</tr>
<tr>
<td>( F_{\text{fs}} )</td>
<td>[N/m]</td>
<td>Specific tangential force in grinding</td>
</tr>
<tr>
<td>( F_{\text{ad}} )</td>
<td>[N]</td>
<td>Axial forces in dressing</td>
</tr>
<tr>
<td>( f_{\text{ad}} )</td>
<td>[m]</td>
<td>Axial feed per revolution of the grinding wheel in dressing</td>
</tr>
<tr>
<td>( F_{\text{nd}} )</td>
<td>[N]</td>
<td>Load on a hydrostatic bearing</td>
</tr>
<tr>
<td>( F_{\text{n}} )</td>
<td>[N]</td>
<td>Normal force</td>
</tr>
<tr>
<td>( F_{\text{nd}} )</td>
<td>[N]</td>
<td>Normal forces in dressing</td>
</tr>
<tr>
<td>( F_{\text{ns}} )</td>
<td>[N]</td>
<td>Normal forces in grinding</td>
</tr>
<tr>
<td>( F_{\text{pre}} )</td>
<td>[N]</td>
<td>Preload force of a hydrostatic bearing</td>
</tr>
<tr>
<td>( f_r )</td>
<td>[Hz]</td>
<td>Rotational frequency of form roll</td>
</tr>
<tr>
<td>( f_{rd} )</td>
<td>[m]</td>
<td>Radial feed per revolution of the grinding wheel in dressing</td>
</tr>
<tr>
<td>( f_s )</td>
<td>[Hz]</td>
<td>Sample frequency</td>
</tr>
<tr>
<td>( F_{\text{t}} )</td>
<td>[N]</td>
<td>Tangential force</td>
</tr>
<tr>
<td>( F_{\text{fd}} )</td>
<td>[N]</td>
<td>Tangential force in dressing</td>
</tr>
<tr>
<td>( F_{\text{fs}} )</td>
<td>[N]</td>
<td>Tangential force in grinding</td>
</tr>
<tr>
<td>( G )</td>
<td>[-]</td>
<td>Grinding wheel wear ratio</td>
</tr>
<tr>
<td>( G_d )</td>
<td>[-]</td>
<td>Form roll wear ratio</td>
</tr>
<tr>
<td>( h_{cu} )</td>
<td>[m]</td>
<td>Maximum uncut chip thickness</td>
</tr>
<tr>
<td>( h_p )</td>
<td>[m]</td>
<td>Height of grinding wheel profile</td>
</tr>
<tr>
<td>( h_{\text{p,rel}} )</td>
<td>[-]</td>
<td>Relative height of grinding wheel profile</td>
</tr>
<tr>
<td>( I_{\text{sa}} )</td>
<td>[A]</td>
<td>Current through dressing electrode</td>
</tr>
<tr>
<td>( I_r )</td>
<td>[kg·m²]</td>
<td>Mass moment of inertia of the dressing spindle rotor</td>
</tr>
</tbody>
</table>
$K_{ic}$ [MPa·m$^{1/2}$] Critical fracture toughness

$K_{ch,ex}$ [€] Total cost of a form roll change when using external regrinding

$K_{ch,in}$ [€] Total cost of a form roll change when using on-machine regrinding

$K_{grind}$ [€] Cost of the grinding wheel consumed in regrinding

$K_{mach}$ [€/hr] Hourly rate of the grinding machine

$K_{op}$ [€/hr] Hourly rate of the operator

$K_{reg,ex}$ [€] Cost to regrind a form roll externally

$K_{roll}$ [€] Cost of purchase of a form roll

$l$ [m] Geometrical contact length

$L$ [m] Grinding length

$n_{max}$ [rpm] Maximum rotational velocity of spindle

$n_{real}$ [rpm] Actual rotational velocity of form roll

$n_{set}$ [rpm] Setpoint for rotational velocity of form roll

$n_d$ [rpm] Rotational velocity of the form roll in dressing

$n_{reg,ex}$ [-] Number of times a form roll can be reground externally

$n_{reg,in}$ [-] Number of times a form roll can be reground on-machine

$n_s$ [rpm] Rotational velocity of the grinding wheel in grinding

$n_{sd}$ [rpm] Rotational velocity of the grinding wheel in dressing

$p_a$ [Pa] Ambient pressure

$p_u$ [Pa] Amplitude of pressure fluctuations caused by high pressure pump

$P_{max}$ [W] Maximum spindle power

$p_{max}$ [Pa] Pressure variation in bearing pocket due to external force

$p_r$ [Pa] Pressure in bearing pocket

$p_{av}$ [Pa] Average pocket pressure when bearing is unloaded

$p_{ax}$ [Pa] Pressure in pocket axial bearing

$p_{rd}$ [Pa] Pressure in bearing pocket in loaded condition

$p_{uld}$ [Pa] Pressure in bearing pocket in unloaded condition

$p_s$ [Pa] Supply pressure
\[ Q_{sb} \quad [m^3/(m\cdot s)] \quad \text{Removed volume of sharpening block per millimeter grinding wheel width per second} \]

\[ Q_{w} \quad [m^3/(m\cdot s)] \quad \text{Removed volume of material per millimeter grinding wheel width per second} \]

\[ q_s \quad [-] \quad \text{Velocity ratio in dressing} \]

\[ q_{s,re} \quad [-] \quad \text{Velocity ratio in regrinding} \]

\[ R_{a} \quad [\mu m] \quad \text{Arithmetic average roughness} \]

\[ r_{A,av} \quad [m] \quad \text{Average radius of body A} \]

\[ r_{A,max} \quad [m] \quad \text{Maximum radius of body A} \]

\[ r_{A,min} \quad [m] \quad \text{Minimum radius of body A} \]

\[ r_{B,av} \quad [m] \quad \text{Average radius of body B} \]

\[ R_{prof} \quad [m] \quad \text{Local grinding wheel profile radius} \]

\[ R_{top} \quad [m] \quad \text{Top radius of the form roll} \]

\[ R_{z} \quad [\mu m] \quad \text{Mean roughness depth} \]

\[ T_{a} \quad [N\cdot m] \quad \text{Acceleration torque of the dressing spindle} \]

\[ t_{a} \quad [^\circ C] \quad \text{Ambient temperature} \]

\[ t_{ch} \quad [hr] \quad \text{Total time for changing the form roll} \]

\[ T_{ex} \quad [N\cdot m] \quad \text{Torque on form roll axis due to external influences} \]

\[ T_{f} \quad [N\cdot m] \quad \text{Friction torque of the dressing spindle} \]

\[ t_{f} \quad [^\circ C] \quad \text{Temperature of the hydraulic fluid} \]

\[ T_{m} \quad [N\cdot m] \quad \text{Torque on form roll axis developed by the form roll drive motor} \]

\[ T_{m,set} \quad [N\cdot m] \quad \text{Set-point value for the torque of the form roll drive motor} \]

\[ t_{min} \quad [m] \quad \text{Minimal wall thickness} \]

\[ T_{process} \quad [N\cdot m] \quad \text{Torque needed in dressing due to the dressing process} \]

\[ T_{r} \quad [N\cdot m] \quad \text{Torque on form roll axis generated by the crushing process} \]

\[ t_{reg,in} \quad [hr] \quad \text{Time spend on regrinding the form roll on the machine} \]

\[ T_{sync} \quad [N\cdot m] \quad \text{Synchronizing torque transferred in contact zone of form roll and grinding wheel} \]

\[ T_{sync,d,max} \quad [N\cdot m] \quad \text{Maximum synchronizing torque transferred in contact zone of form roll and grinding wheel when slip is present} \]
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{sync,max}$</td>
<td>[N·m]</td>
<td>Maximum synchronizing torque transferred in contact zone of form roll and grinding wheel</td>
</tr>
<tr>
<td>$T_{sync,s,max}$</td>
<td>[N·m]</td>
<td>Maximum synchronizing torque transferred in contact zone of form roll and grinding wheel when bodies are synchronized</td>
</tr>
<tr>
<td>$T_δ$</td>
<td>[N·m]</td>
<td>Torque mismatch in crush dressing</td>
</tr>
<tr>
<td>$U_d$</td>
<td>[-]</td>
<td>Overlap ratio in dressing</td>
</tr>
<tr>
<td>$U_{d,tho}$</td>
<td>[-]</td>
<td>Theoretical overlap ratio in dressing</td>
</tr>
<tr>
<td>$U_{sb}$</td>
<td>[V]</td>
<td>Voltage over dressing electrode (electro contact dressing)</td>
</tr>
<tr>
<td>$v$</td>
<td>[m/s]</td>
<td>Velocity</td>
</tr>
<tr>
<td>$V'_{sb}$</td>
<td>[m$^3$/m]</td>
<td>Removed volume of sharpening block per millimeter grinding wheel width</td>
</tr>
<tr>
<td>$V'_w$</td>
<td>[m$^3$/m]</td>
<td>Specific removed workpiece volume</td>
</tr>
<tr>
<td>$v_{av}$</td>
<td>[m/s]</td>
<td>Average velocity in the contact zone of two bodies in rolling contact</td>
</tr>
<tr>
<td>$V_{ax,0}$</td>
<td>[m$^3$]</td>
<td>Total volume between restrictor and lands of the axial bearing</td>
</tr>
<tr>
<td>$V_{ax,pocket}$</td>
<td>[m$^3$]</td>
<td>Volume of the axial bearing pocket only</td>
</tr>
<tr>
<td>$V_{axis}$</td>
<td>[m$^3$]</td>
<td>Volume connected to the axial bearing pocket in the form roll axis</td>
</tr>
<tr>
<td>$V_{chan}$</td>
<td>[m$^3$]</td>
<td>Volume connected to the axial bearing pocket located in channels</td>
</tr>
<tr>
<td>$v_t$</td>
<td>[m/s]</td>
<td>Feed rate in grinding</td>
</tr>
<tr>
<td>$v_{osc}$</td>
<td>[m/s]</td>
<td>Oscillation velocity in regrinding</td>
</tr>
<tr>
<td>$v_{swiv}$</td>
<td>[º/s]</td>
<td>Swivel velocity in regrinding</td>
</tr>
<tr>
<td>$v_{fad}$</td>
<td>[m/s]</td>
<td>Axial feed rate in dressing</td>
</tr>
<tr>
<td>$v_{ads}$</td>
<td>[m/s]</td>
<td>Feed rate of dressing electrode (electro contact dressing)</td>
</tr>
<tr>
<td>$v_{ld}$</td>
<td>[m/s]</td>
<td>Feed rate along the contour in dressing</td>
</tr>
<tr>
<td>$v_{rd}$</td>
<td>[m/s]</td>
<td>Radial feed rate in dressing</td>
</tr>
<tr>
<td>$v_{frd}$</td>
<td>[m/s]</td>
<td>Form roll surface velocity in dressing</td>
</tr>
<tr>
<td>$V_{rd}$</td>
<td>[mm$^3$]</td>
<td>Form roll wear volume in dressing</td>
</tr>
<tr>
<td>$v_{rd,initial}$</td>
<td>[m/s]</td>
<td>Initial velocity of the form roll</td>
</tr>
<tr>
<td>$v_{rd,sett}$</td>
<td>[m/s]</td>
<td>Set-point value for the velocity of the form roll in the controller</td>
</tr>
</tbody>
</table>
\( v_s \) [m/s] Grind wheel surface velocity
\( V_s \) [m^3] Grind wheel wear volume in grinding
\( v_{s,\text{re}} \) [m/s] Grind velocity in regrinding
\( v_{sd} \) [m/s] Grind wheel surface velocity in dressing
\( V_{sd} \) [m^3] Grind wheel wear volume in dressing
\( v_{\text{sync}} \) [m/s] Synchronized velocity in crushing
\( V_{\text{thrust}} \) [m^3] Volume connected to axial bearing pocket located in the thrust disk
\( V_w \) [m^3] Removed workpiece volume
\( v_\delta \) [m/s] Velocity difference between form roll and grind wheel
\( \alpha \) [º] Angular position of form roll axis
\( \beta \) [º] Profile angle
\( \beta_{\text{rad}} \) [Pa^{-1}] Compressibility of the hydraulic fluid
\( \beta_{\text{max}} \) [º] Maximum profile angle
\( \Delta a \) [m] Distance between axis of form roll and grinding wheel
\( \delta_r \) [m] Radial form roll wear per dressing pass
\( \delta_{r,\text{tot}} \) [m] Total radial form roll wear
\( \Delta r_s \) [m] Radial grinding wheel wear
\( \Delta r_{s,\text{ini}} \) [m] Initial radial grinding wheel wear
\( \Delta v \) [m/s] Velocity variation on a grinding wheel profile
\( \delta_Y \) [m] Vertical Y-position of the form roll
\( \theta_{\text{top}} \) [º] Top angle of form roll
\( \lambda_s \) [m] Cut-off from high-pass filter used in roughness measurements
\( \mu \) [-] Coefficient of friction
\( \mu_d \) [-] Dynamic coefficient of friction
\( \mu_s \) [-] Static coefficient of friction
\( c_{\text{rad}} \) [1/m] Radial bearing stiffness factor
\( \omega_{\text{pump}} \) [rad/s] Angular velocity of the high pressure pump
\( \omega_{rd} \) [rad/s] Angular velocity of the form roll during dressing
\( \omega_{rd,0} \) [rad/s] Angular velocity of the form roll at the start of a
measurement series

\[ \omega_{sd} \quad [\text{rad/s}] \quad \text{Angular velocity of the grinding wheel during dressing} \]

\[ \omega_{sd,0} \quad [\text{rad/s}] \quad \text{Angular velocity of the grinding wheel at the start of a measurement series} \]

**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE</td>
<td>Acoustic emission</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>Aluminum oxide</td>
</tr>
<tr>
<td>CBN</td>
<td>Cubic Boron Nitride</td>
</tr>
<tr>
<td>CCW</td>
<td>Counter clockwise</td>
</tr>
<tr>
<td>CIFB</td>
<td>Cast iron fiber bonded</td>
</tr>
<tr>
<td>Co</td>
<td>Cobalt</td>
</tr>
<tr>
<td>CVD</td>
<td>Chemical vapor deposition</td>
</tr>
<tr>
<td>CW</td>
<td>Clockwise</td>
</tr>
<tr>
<td>D</td>
<td>Diamond</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>ECD</td>
<td>Electro chemical dressing</td>
</tr>
<tr>
<td>ECDD</td>
<td>Electro contact discharge dressing</td>
</tr>
<tr>
<td>ECM</td>
<td>Electro chemical discharge machining</td>
</tr>
<tr>
<td>EDM</td>
<td>Electrical discharge machining</td>
</tr>
<tr>
<td>ELID</td>
<td>Electrolytic in-process dressing</td>
</tr>
<tr>
<td>GW</td>
<td>Grinding wheel</td>
</tr>
<tr>
<td>HK</td>
<td>Knoop hardness scale</td>
</tr>
<tr>
<td>HRC</td>
<td>Rockwell Hardness scale C</td>
</tr>
<tr>
<td>HSS</td>
<td>High Speed Steel</td>
</tr>
<tr>
<td>HV</td>
<td>Vickers hardness scale</td>
</tr>
<tr>
<td>LS</td>
<td>Least squares</td>
</tr>
<tr>
<td>NC</td>
<td>Numerical Control</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------------------</td>
</tr>
<tr>
<td>NC</td>
<td>Numerical control</td>
</tr>
<tr>
<td>NRRO</td>
<td>Non-repeatable run-out</td>
</tr>
<tr>
<td>PCBN</td>
<td>Polycrystalline cubic boron nitride</td>
</tr>
<tr>
<td>PCD</td>
<td>Poly Crystalline Diamond</td>
</tr>
<tr>
<td>PCD</td>
<td>Polycrystalline diamond</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable logic controller</td>
</tr>
<tr>
<td>PSD</td>
<td>Power spectral density</td>
</tr>
<tr>
<td>RRO</td>
<td>Repeatable run-out</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscopy</td>
</tr>
<tr>
<td>SIC</td>
<td>Silicon Carbide</td>
</tr>
<tr>
<td>WC</td>
<td>Tungsten carbide</td>
</tr>
<tr>
<td>WEDM</td>
<td>Wire electrical discharge machining</td>
</tr>
</tbody>
</table>
1 Introduction

In this chapter an introduction on the subject of this thesis is given. The field of research is approached starting from the general trends in precision manufacturing narrowing down to precision grinding operations and focussing on conditioning of diamond grinding wheels.

From the first moments man started creating artefacts there has been a strong drive to improve the performance of these parts. Manufacturing is one of the main fields enabling the developments in technology. Precision manufacturing deals with the fabrication of parts with high accuracies.

In precision manufacturing several trends are visible:

- Integration of functions in one single part leading to less complex assemblies but more complex parts
- Decreasing part tolerances (higher accuracy)
- Cost reduction
- Use of advanced materials to meet the increasing demands on products
- Smaller production series (due to higher product diversity and smaller product life cycle)

This shows directly the challenges for precision manufacturing engineering and research. Cost reductions are a driving force behind the elimination of process steps, but also tight part tolerances ask for the machining of critical part features in one machine set-up. Combining this with the increasing complexity of products there is a trend visible towards flexible, versatile, accurate and autonomous machines. The use of advanced materials is another main challenge in precision manufacturing. Apart from the commonly used metals (e.g. steels and aluminium), engineered materials like ceramics and tungsten carbide based hardmetals are increasingly used. These materials show a, before, unknown hardness and wear resistance, often combined with attractive thermal and electrical properties. Accurate machining of these very hard and brittle materials is a difficult task and the focus of this work.

Grinding has proven to be one of the few available manufacturing technologies that can efficiently and accurately machine these hard materials. Grinding as a machining operation has a long history; already in the stone ages man found out that it is possible to remove material by rubbing a workpiece against sandstone. With the invention of bronze and later iron and steel, grinding gained importance to shape these materials. In these early times sharp edges for knives and weaponry were probably the most common application for grinding. Going through history quickly man...
discovered that brass and bronze could be machined with steel cutting tools. These steel tools were made by grinding. In the nineteenth century the temperature resistant high speed steel (HSS) was invented to machine steel followed by the invention of the very hard (tungsten carbide based) hardmetal in the 20th century. Always grinding has been the method of choice to shape these hardest of materials. Nowadays there still remain materials that cannot be cut with a so-called defined cutting edge (knife-type tool) like for example milling, turning and drilling. To manufacture high accuracy parts in these hard materials, grinding is the solution. The grinding tools also had to develop to keep up with the changing workpiece materials. From sandstone, through corundum (aluminiumoxide) and carborundum (siliconcarbide), the hardness and wear resistance of grinding grains improved to the nowadays frequently used super-abrasives: cubic boron nitride and diamond.

As the hardest of materials diamond is an excellent abrasive. However the very nature of grinding: wear of the grinding wheel, poses another challenge: preparation of the grinding wheel. As the wheel is composed of diamond particles it is extremely difficult to condition the grinding wheel into its desired shape. Creating the complex profiles, which have to be ground in the workpiece, into the super-abrasive grinding wheel with the demanded accuracy is a prerequisite for precision grinding. However this task has only been partly solved by the currently available technologies.

Therefore this thesis will focus on the development of a conditioning process for super-abrasive grinding wheels that can satisfy the needs of industry as mentioned above.

In the next chapter a basic understanding of grinding and grinding tools is given. In chapter 3 the state-of-the-art in super-abrasive grinding wheel conditioning is discussed extensively. In chapter 4 the project is defined more sharply and the goals of the work are identified. The remaining chapters will deal with the research performed to achieve these research goals. Basically the work can be divided into the development of the necessary equipment (chapters 6 and 7) and the development of a process strategy and the process itself (chapter 8, 9 and 10).
2 Grinding and grinding tools

Abrasive processes are amongst the oldest manufacturing processes. Grinding makes use of a rotating circular tool containing abrasive particles that are bonded (fixed) in some way to the rotating body. The rotating motion creates the necessary cutting speed \(v_s\) to remove material from the workpiece by an abrading action. This is illustrated for circumferential grinding in Figure 2-1. The use of abrasives particles that have undefined shapes distinguishes grinding from the machining operations with defined cutting edges like milling, turning and drilling. Other operations with undefined cutting edges include polishing and honing and also the class of loose abrasive processes (e.g. air blasting and abrasive waterjet cutting).

![Figure 2-1: Schematic of circumferential grinding [Mari07]](image)

From Figure 2-1 some factors that influence the grinding process can be seen:

- The workpiece material; hardness, toughness, heat conductivity, brittleness, these properties all influence the grinding process.
- The grinding fluid used to lubricate and cool the grinding zone, pure oils are used when optimal lubrication is needed. Water based solutions of oil are preferred when a high cooling effect is important.
- The grinding machine: has to handle the cutting forces and position the workpiece and grinding wheel relative to each other to achieve the desired accuracy.
- The grinding wheel itself which will be studied in more detail below.
- Compared to other abrasive processes like lapping, honing and super finishing the cutting speeds used in grinding are high (10 - 200 m/s). However loose abrasive processes use even higher speeds, e.g. in abrasive waterjet cutting, speeds of over 700 m/s are not uncommon [Hoog00].
2.1 Material removal in grinding

The material removal mechanism in grinding is illustrated below in Figure 2-2. Due to the combined motion of the grinding wheel and the workpiece the grinding grain enters the workpiece surface and removes a small chip from the workpiece. Three different phases can be distinguished during the contact between workpiece and grain: first there is only some friction and elastic deformation. In the next phase plastic deformation occurs in the workpiece material and material outbursts are formed (often referred to as ploughing), but no chip is formed. In the last phase the deformations become so large that material is actually separated from the workpiece creating a chip and thereby affecting material removal.

In the figure another important characteristic of abrasive processes can be seen: the highly negative rake angle of the tool (grain). This negative rake angle creates high passive forces (indicated in the figure by $F_{ns}$) and thereby a lot of friction and deformation. These can lead to thermo and mechanical damage of the (sub-)surface and need serious attention when laying out grinding processes.

![Figure 2-2: Mechanism of material removal in grinding, after Klocke and König [Kloc05]](image)

The accuracy of the grinding process can be contributed to the cumulative effect of all grinding grains and the fact that the small grains can make very small chips which cannot be achieved with defined cutting edges. The large amount of cutting edges makes that failure of a single cutting edge does not strongly affect the accuracy while for example in turning this would be directly reflected in the workpiece surface.

Characteristic for grinding is also the wear of the tool. This is an ambivalent property: on the one hand the fracture and removal of grains leads to new sharp grains being exposed thereby maintaining the cutting ability of the wheel. On the other hand this wear leads to a loss of accuracy.
and roundness of the wheel and cost. In every grinding process a balance has to be found between these effects.

2.2 Grinding tools

As mentioned in the previous paragraph a grinding tool consists of abrasives bonded to a rotating body. The abrasive grains are the most striking part of a grinding tool. However the bond that bonds the grains together or to the body is just as important. Many grinding tools also have a certain amount of porosity that creates the necessary chipspace to accommodate the chip created during grinding and facilitate the transport of grinding fluid into the contact zone. In Figure 2-3 below a schematic representation of the grinding wheel composition is shown together with the wear mechanisms of a grain.

![Figure 2-3: Grinding wheel structure and wear mechanisms (after [Mari07])](image)

Shown is a structure of a wheel with multiple layers of abrasives. It is also possible to bond a single layer of abrasives directly to a body. These so-called single-layer grinding wheels are not further discussed here as they are not dressable (see chapter 3) and therefore of no relevance to this work. There are basically three different wear mechanisms for a grinding grain:

- **Grain pullout**: a complete grain is removed from the grinding wheel due to fracture of the supporting bond material or failure of the interface between the grain and the bond.
- **Grain breakdown**: small portions of the grain are overloaded and break off the grain creating new sharp cutting edges.
- **Grain wear**: the grain wears down due to the abrasive contact with the workpiece, leading to flat and dull cutting edges resulting in high cutting forces and temperatures and smooth surface finishes.

These effects will occur simultaneously during grinding and when balanced well a grinding wheel with low wear and good cutting ability can be designed.

Below the three major components of a grinding wheel, the abrasive, the bond and the porosity, are studied in more detail.
2.2.1 Abrasive

Abrasives come in many different materials, sizes, qualities and shapes. Abrasive materials are divided in the conventional abrasives like alumina (aluminium-oxide, \( \text{Al}_2\text{O}_3 \)) and Silicon Carbide (SiC) and the super-abrasives cubic Boron Nitride (CBN) and diamond. In Figure 2-4 the hardness and toughness of these materials are compared to some workpiece materials. Clearly CBN and diamond have the highest hardness values. When it is noticed how close the hardness of tungsten carbide based hardmetals is to alumina and even SiC the need for the use of diamond to grind this material becomes clear. CBN finds its major use in grinding HSS and tool steels as diamonds cannot be used for these materials due to the diffusion of carbon into the iron workpiece (at higher temperatures), degrading the diamond to soft graphite, resulting in accelerated wear of the diamond grains.

![Figure 2-4: Hardness and toughness of abrasives used in grinding wheels [Hell93]](image)

The grain sizes used in grinding wheels range from several \( \mu \text{m} \) to some tenth of a mm, depending on the application, in general a grain as "large as possible and small as necessary" has to be chosen. For super-abrasive grains the grain sizes are indicated by their average grain diameter in \( \mu \text{m} \), e.g. D46 indicates diamond grains with an average diameter of 46 \( \mu \text{m} \) while B46 is used for CBN grains of that size.

Grains come in many different shapes, especially when they are man-made the shape can be controlled. Super-abrasives can be made from very blocky and solid to irregular and sharp. Furthermore the friability of the grains is controlled and often coatings are applied to improve the adhesion between bond and grain (e.g. Nickel coatings on diamond grains for resin bond materials).

The amount of abrasive in a grinding wheel is very important as it determines the amount of cutting edges. For diamond grinding wheels this is indicated by the concentration, e.g. C100. The figure 100 denotes that a 25\% volume fraction \( (= 4.4 \text{ carat/cm}^3 = 0.88 \text{ g/cm}^3) \) of the abrasive layer is diamond. The scale is linear, therefore C50 denotes 12.5\% diamond. A consequence of the fact that this scale is defined based on the diamond volume is that, when the concentration is kept constant,
the amount of cutting edges per unit volume increases when the average grain size is chosen smaller. Therefore the concentration of very fine grain grinding wheels is generally chosen lower.

### 2.2.2 Bond

The bond acts as glue to, used are resin, metal and vitrified bonds. Metal bonds have the highest grain retention capacity resulting in very low wear but are very hard to condition and result in high grinding forces. Resin bonded wheels are cost effective and more elastic, making them more impact resistant however tool wear is much higher. A drawback of both these bond systems is the lack of chip space as these bonds generally have little to no porosity. Vitrified bonds can be very hard too and behave brittle. In general vitrified bonds are more expensive to manufacture but their properties can be varied within a wide range. Advantages of vitrified bonds include their porosity (see section 2.2.3 below) and high stiffness. The damping properties of the bond also influence its behavior. Resin bonds show good damping properties which can be advantageous is certain applications. Vitrified and metal bonds show little damping.

The capacity of a grinding wheel to hold a grain is referred to as hardness, work hardness or grinding hardness. This is not directly related to hardness of materials, although some measurement methods for grinding wheels use indentation testers like the ones used for material hardness testing. The hardness of grinding wheels is denoted by a letter ranging from A (extremely soft) to Z (extremely hard), while I to N is a more common range. However only this relative scale is commonly used, every manufacturer defines a measurement system, unit and calibration by itself. Therefore comparison of wheels on the basis of hardness is generally only possible among grinding wheels of the same manufacturer and type. In practice comparison of wheels is mostly based on their grinding performance.

### 2.2.3 Porosity

Porosity is added to grinding wheels to create chip space and to improve wetting of the grinding zone with grinding fluid.

In vitrified wheels porosity can be increased with pore builders up to 40 % volume. Sometimes pores are created by adding a very soft component to the bond, this is for example done when graphite particles are added to bronze bonds. These particles are quickly removed during grinding, creating pores. The addition of hollow glass spheres is another way to add pores to a bond. Another effect of porosity is that it will make the grinding wheel behave more brittle, the importance of which will become clear in the following chapters.

Apart from the amount of porosity the size and distribution of the pores is also used to control the properties of the wheel. Larger pores are for example appreciated to transport grinding fluid into the grinding zone. The information provided by manufacturers is generally not more than a qualitative indication.
The preceding sections gave a basic insight in grinding and super-abrasive grinding tools. The following chapter gives an extensive overview of the state-of-the-art in super-abrasive grinding wheel conditioning.

2.3 Grinding of complex shaped parts

To create parts with complex cross sections by grinding there are two basic methods in use. The first method is to create the (negative shape of the) needed profile in the grinding wheel and then directly grind the full profile into the workpiece. Grinding is then mostly done in creep feed grinding mode resulting in a relatively low grain load leading to good shape holding ability of the grinding wheel. The second option is to use a grinding wheel with a defined and small contact area, e.g. a toroidal wheel and creating the profile by making many passes controlled by the numerical control of the machine. An advantage of this approach is the flexibility in the achievable workpiece shapes [Bier08]. Because many passes are needed in this grinding method, pendulum grinding and speed stroke grinding are the preferred methods, leading to lower (total) grinding forces which can be advantageous for the accuracy and integrity of high accuracy products.
3 Super-abrasive grinding wheel dressing

In this chapter available methods to dress super-abrasive grinding wheels are reviewed. First in section 3.1 grinding wheel conditioning is defined. Subsequently section 3.2 introduces the mechanical dressing methods while the thermal and chemical based methods are covered in section 3.3. Section 3.4 concludes with a reflection on the applicability of all methods to profile super-abrasive grinding wheels.

3.1 Grinding wheel conditioning: definitions and relations

Under grinding wheel conditioning everything needed to bring a grinding tool into a useable state for first use and to keep it in a cutting condition is regarded. This is illustrated in Figure 3-1 which shows the relations and functions of the different tasks in conditioning.

Conditioning consists of three main functions: creating the macro geometry, called truing for a straight profile and profiling for a profiled wheel [Salj90]. Removal of run-out of the grinding wheel is included in this operation: the wheel is made to "run true". Secondly the micro geometry of the grinding wheel has to be created, this is done in sharpening. Sharpening exposes the grains of the grinding wheel by removing the binder material, thereby creating the necessary chip space between the grains. Creating new, sharp cutting edges, e.g. by grain fracture, is also part of sharpening [Töns92]. Creating macro and micro geometry together is referred to as dressing. The third task in conditioning is cleaning: removal of debris (chips, dressing debris) from the grinding wheel. These three tasks are in practice often not clearly separated or identifiable. Cleaning is often given less attention as the necessary cooling fluid beam in grinding is generally sufficient. Furthermore technologies to create the macro geometry also influence the micro geometry, sometimes in such a
way that a separate sharpening action becomes superfluous. The term dressing is used by some authors in the more restricted meaning of sharpening which can be confusing. The following section details the dressing of super-abrasive grinding wheels. Cleaning is not covered in this work.

Dressing of super-abrasive grinding wheels is a challenge and many processes have been suggested that are often restricted in their use. An insight in the existing methods and their limitations and applications is needed to define further research in this field. The following sections discuss existing technologies to dress super-abrasive grinding wheels, in a structured way. For every technology the dressing mechanism (material removal mechanism), kinematics, profile generation, used tools, application area and restrictions are discussed. There are different ways to group the different dressing processes, e.g. based on the physical principle of material removal, the kinematics, the shape of the tool, profile generation method etc. Below two large subdivisions are made: mechanical processes (3.2) and thermal and chemical processes (3.3).

3.2 Mechanical dressing

Dressing methods using fracture, deformation and separation due to mechanical force and/or abrasive action as material removal mechanism, are defined here as mechanical dressing.

3.2.1 Steel dressing

The most straightforward method to remove run-out (truing) and create chip space (sharpening) on a super-abrasive grinding wheel is to grind a soft steel (e.g. St 37) workpiece. Soft steel is used because it results in long chips. The soft chips will not dull the super-abrasive cutting edges significantly, but wear out the bond material due to the abrasive action when the chip rubs against it. This abrading action creates chip space and when the process is continued it removes grains because the grain retention capacity of the bond is reduced to such an extent that the grain will drop out of the binder due to the cutting force [Gärt82]. When grinding the steel workpiece a low cutting speed \( v_c \) with relatively high depth of cut \( a_e \) with lower feeds \( v_f \) are used to create long chips. Exact values are dependent on the type of wheel used (grain size, binder material and hardness) and its initial condition. Steel dressing is only used for truing and sharpening, profiles cannot be generated. A disadvantage is the long truing time. Advantages are its simplicity, low cost and lack of special tooling. The main application is on super-abrasive grinding wheels with less wear resistant bond materials, in order of application: resin, metal, vitrified bonds. Notter and Shafto used steel rolls instead of a steel block to dress large resin bonded super-abrasive wheels, to reduce dressing time [Nott79]. Huang [Huan01] also describes the use of mild steel rolls (diameter 100mm and width 30 mm) mounted on a driven dresser to dress a D126 vitrified diamond grinding wheel. Positive dressing speed ratios \( q_d \) were used, whereby low speed ratios \( q_d < 0.25 \) led to a sharpening action and higher ratios \( q_d > 0.5 \) to a truing action. \( q_d \) is defined as the ratio of the circumferential speeds of the dressing tool and the grinding wheel:
This is explained by a change of the material removal mechanism from bond wear at low speed ratios to brittle fracture (see also 3.2.9) at higher speed ratios. Huang used a depth of cut of \( a_d = 0.2-3 \ \mu m \), axial feed speeds \( v_{f_d} \) of 100-300 mm/min, and speed ratios \( q_d \) of 0.17 to 0.63. Wheel run-out is reduced to little below 10 \( \mu m \) which is generally considered insufficient for super-abrasive precision grinding. Sawluk mentions the use of two cylindrical steel workpieces rotating in opposite direction that are ground in an external cylindrical grinding process [Sawl74] to dress resin bonded CBN grinding wheels. In this way a grain on the grinding wheel is loaded from two directions, leading to removal of the bond material on both sides and an alternating mechanical load on the grain, both leading to an increased efficiency of the dressing process. An interesting use of steel dressing is mentioned by Koch [Koch92] who uses the affinity of steel and diamond to dull the diamond grains. This is done for ductile grinding of optical glasses were highly negative rake angles are required.

### 3.2.2 Free grinding

The term free grinding is used when a grinding wheel is put into use with reduced grinding parameters \( (a_u, v_u) \) after truing. During this period the grinding process itself should create the needed chipspace in a way comparable to steel grinding. Free grinding is therefore only a sharpening operation and most effective for rather ductile materials that create large enough chips to wear out the bond material. It is commonly used with CBN grinding wheels, as CBN is used for machining the (relatively) ductile hardened steels. Klocke and Stüff used free grinding on vitrified CBN grinding wheels and compared it to block sharpening (see 3.2.3). They used a stepwise increase of the material removal rate \( (Q'_w) \) showing that free grinding is a more gentle process delivering better workpiece qualities [Kloc95a], [Stu96].

### 3.2.3 Abrasive block sharpening

The block sharpening process is used to sharpen grinding wheels by feeding an abrasive block into the grinding wheel with a specified specific volume per dress \( (V'_s_b) \) and at a specified specific volumetric rate \( (Q'_s_b) \). Sharpening blocks generally consist of a conventional abrasive (SiC or Al₂O₃) and a binder material. Normally a grinding wheel is first profiled or trued and then, when necessary, block sharpening is applied to open up the grinding wheel surface and create chip space. For example for vitrified bonded CBN grinding wheels rubber bonded SiC sharpening blocks have proved their value [Kloc94a]. When compared to free grinding the grinding wheel topography is much more influenced (damaged) with block sharpening, disturbing the effect of the preceding profiling process and blunting the grains. The advantage of block sharpening is found in its speed and cost effectiveness compared to free grinding. Furthermore block sharpening can be done by
hand making its use very convenient. The need for a controlled infeed of the sharpening block to achieve a reproducible result is stressed by Spur [Spur87]. The sharpening volume per second per mm grinding wheel width, \( Q'_{Sb} \), determines the sharpening effect. The end of the sharpening operation can be detected when the sharpening (normal) forces \( F_{nd} \) are monitored; these forces will drop to a stable level when sharpening is completed [Inas89], [Spur87]. For resin bonded CBN wheels much larger values for \( V'_{Sb} \) and \( Q'_{Sb} \) are used due to the lack of porosity in these bond systems. A different sharpening material is proposed by Nakano et al. which makes use of a glass fiber reinforced resin block to continuously sharpen a resin bonded diamond wheel for cutting-off a Si-Al-O-N ceramic. This sharpening (and cleaning) method leads to significantly lower wear of the grinding wheel [Naka89].

### 3.2.4 Wire brush sharpening

Instead of using bonded abrasives, wire brushes can be used to set back the bond material and clean the grinding wheel surface. Inasaki observed a strong sharpening effect on resin bonded CBN grinding wheels and integrated rotary steel wire brushes with a diamond rotary dresser [Inas90] (see also 3.2.8). Barnard mentions reduction of dressing times by half due to the use of a hardened steel wire brush [Barn89a] in crush dressing (see 3.2.9).

### 3.2.5 Jet dressing

Several authors have investigated the effect of the use of jets on the grinding wheel structure. The goals of these methods are cleaning and sharpening. Ishikawa used dry blasting at 0.4 MPa air pressure with 70 µm grit size alumina to open up the structure of a vitrified CBN wheel [Ishi91]. This results in more stable grinding forces and avoidance of the higher grinding forces generally seen directly after truing due to a closed grinding wheel surface. Tönshoff used SiC abrasive at 0.4 MPa air pressure also on a vitrified CBN wheel. A waterjet with abrasives is used by Shen [Shen01] to sharpen and clean a metal bonded diamond grinding wheel while Saljé uses 10-20 MPa on hard resin and metal bonded super-abrasive wheels [Salj83]. Hirao uses a plain water jet at 107 MPa to dress the surface of a CBN grinding wheel [Hira98]. Both Shen and Hirao use the water jet in-process.

### 3.2.6 Stationary diamond dressing

Stationary diamond dressing can be described as a turning operation performed on the grinding wheel with a chisel type tool equipped with a diamond tip, Figure 3-2. This operation is very common to dress conventional grinding wheels. Profiles can be created by controlling the path of the tool e.g. by the numerical control, making it very flexible. An important parameter to control the grinding wheel topography is the ratio of the dresser width, \( b_d \), and the axial feed per revolution of the grinding wheel, \( f_{ad} \), called the overlap ratio, \( U_d \):
Practically $U_d$ defines how often a point on the grinding wheel surface is acted upon by the dressing tool. $U_d$ values smaller than one have little practical relevance as this is equal to making a thread in the wheel surface. In general very high values of $U_d$ lead to the formation of a blunt grinding wheel topography. Values in the range of $U_d = 1-10$ are common, where smaller values are used to get an aggressive wheel surface, while higher values will result in smoother workpiece surface finish.

For super-abrasive grinding wheels single stationary diamond dressing is used to a very limited extent due to high wear of the tool.

Figure 3-2: Single point diamond dressing: a) kinematics and b) definitions

Reported applications are generally concerned with CBN wheels, the material removal is primarily due to fracturing of the bond material but also grains. Barnard mentions profiling of CBN wheels with a specially developed soft vitrified bond with a diamond chisel, however no wear results are given [Barn85]. Yokogawa states that the use of this method is satisfactory for a vitrified CBN wheel (diameter 300mm, width 10 mm) with a straight profile, but not for wider or profiled wheels because of the high wear [Yoko92]. Syoji tested two different stationary diamond dressing methods on a D54 vitrified diamond grinding wheel: 1) single point diamond dressing (1.5 ct diamond) and 2) a diamond impregnated stationary dresser with D301 diamond grains [Syoj90]. In both cases the depth of cut $a_{pd}$ (see Figure 3-2) was 10 $\mu$m, the grinding wheel speed $v_{sd} = 25$ m/s and the traverse speed $v_{fad} = 100$ mm/min (at $d_s = 200$ mm). The diamond impregnated tool (diameter 6 mm) proved to be very efficient: it trued the wheel quickly and with 1 $\mu$m resulting run-out. However the progressing wear of the tool led to wear flats resulting in higher truing forces and chatter marks (undulations) on the wheel surface and a run-out not better than 2-3 $\mu$m. The single point diamond tool showed a more consistent behavior and was able to remove wheel run-out repeatedly to almost zero $\mu$m. However when used in grinding, the wheels prepared with both tools
showed very high normal forces (three times higher compared to abrasive dressing, 3.2.7), due to the flattened edges of the diamond grains. Furthermore the wear of the single point diamond dresser is too high to be usable. Therefore single point dressing tools find little application for super-abrasive wheels; however when combined with a laser (see section 3.3.5) this might prove an effective method.

### 3.2.7 Rotary abrasive dressing

One of the most common methods to true, sharpen and profile super-abrasive grinding wheels is to actually grind the super-abrasive grinding wheel with a conventional (often vitrified SiC) grinding wheel. This process is basically a circular grinding process, see Figure 3-3, the tool wear of the SiC wheel is very high.

![Figure 3-3: Principle of rotary abrasive dressing](image)

Material removal of the super-abrasive wheel is effected by abrading the bond material between the grains, ultimately resulting in the removal of the grain. Rotary abrasive dressing is most commonly employed with a SiC wheel mounted on a centrifugal braking device: the super-abrasive wheel drives the SiC wheel by friction which is in its turn decelerated with a centrifugally actuated brake. This braking action creates a speed difference between the two tools. When the right kinematics is available in the machine, profiles can also be made with this process. The achievable profiles are limited because of the extremely high wear of the SiC tool. Straight profiles, outer radii, and shoulder profiles can be made [Gärt82]. The wear of the SiC wheel is averaged out over the width of the wheel by an oscillating axial motion, see Figure 3-3. Brake truers naturally operate only with positive speed ratios ($0 < q_d < 1$) while electrically driven dressers can be operated at positive as well as negative (e.g. [Syoj90]) $q_d$ values. Huang [Huan01] uses a mesh 80 SiC dressing wheel (average grain size of 252 µm) to dress a D126 vitrified diamond grinding wheel employing a depth of cut $a_{cut}$ of 0.2-30 µm, axial feed speeds $v_{fad}$ of 100-300 mm/min, and speed ratios $q_d$ of 0.2 to 0.63. These settings influence the resulting grinding wheel topography. When the wheel is dressed too gently no chipspace is created and the super-abrasive grains get blunt effecting low surface roughness and high grinding forces and temperatures that can damage the (sub-)surface of the
workpiece. Rotary abrasive dressing is the most common way to dress super-abrasive tools, especially diamond tools with all bond systems, including dressing of single layer galvanic bonded diamond wheels.

### 3.2.8 Rotary diamond dressing

Instead of using the aforementioned conventional abrasives to dress super-abrasive grinding wheels, diamonds can also be used in the dressing tool. By using a high diamond concentration, large grain size and hard bond system the wear of the dressing tool can further be reduced. Due to the limited wear more accurate and complex profiles can be created.

**Rotary diamond profile dressing**

To profile CBN grinding wheels, diamond profile rolls, containing the negative of the profile demanded in the grinding wheel, can be used (Figure 3-4a). The roll is ground with the grinding wheel in a circular grinding process, thereby copying the profile of the roll into the grinding wheel. Advantages are that the wear surface of the roll is large, the profile accuracy is mainly determined by the profile roll and profiling can be done very quickly. Disadvantages are that an expensive tool is needed for every profile making this process mainly suitable for large series production. Furthermore wear of the profile roll cannot be compensated for and the dressing forces are relatively high which the machine should be able to handle. This makes profile dressing only applicable for large production volumes [Kloc87]. Stuff controlled the grinding wheel topography with the speed ratio ($q_d = -0.7$ till $0.8$), the radial feed per revolution ($f_{rd} = 0.05 - 0.8 \, \mu m/rev$) and the amount of revolutions of the profile roll at the end of a dressing operation ($0 - 50$ revolutions). Large positive values of the speed ratio resulted in splitting of the grains while low and negative values led to flattened grains. Reduction of radial feed decreased workpiece surface roughness [Stuf96]. For diamond grinding wheels the wear of the profile roll is such high that the application is limited.

**Figure 3-4: Rotary diamond dressing**

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Rotary diamond form dressing

A more flexible profiling method is rotary diamond form dressing (Figure 3-4b), in which a diamond form roll, with a width considerably smaller than the grinding wheel, is moved along the grinding wheel profile with the aid of the numerical path control. The material removal mechanism is comparable to rotary diamond profile dressing. Due to the smaller contact width the dressing forces are smaller. Diamond form dressing is very effective and commonly used on CBN grinding wheels, on diamond grinding wheels its use is gaining importance. The used dressing tools have diamonds in a very hard and wear resistant bond, mostly metal based [Lier02]. The lower hardness of the CBN abrasives compared to diamond leads to acceptable life of the dressing tool and good accuracy of the dressed grinding wheel. When dressing diamond the wear is significant and has to be taken into account when laying out this process. For both super-abrasives the bond system of the grinding wheel should be adopted to this process. The wear of the dressing tool is generally expressed by the dressing wear ratio, \( G_d \), which is defined as:

\[
G_d = \frac{V_{sd}}{V_{d}}
\]

(3-3)

In which \( V_{sd} \) is the volume removed from the grinding wheel and \( V_{d} \) the wear volume of the dressing tool.

Because of the relevance of form dressing as a profiling method for super-abrasives an overview of the research in this area is presented below and separated between CBN grinding wheels and diamond grinding wheels.

Dressing of CBN grinding wheels with diamond form rolls is studied by many authors [Alth81], [Warn90], [Ishi91], [Yoko92], [Töns92], [Töns93], [Köni94], [Töns95], [Kloc95b], [Kloc95a], [Schu96], [Shih00], showing the importance and potential of this process. A major application area for this technology is the (automated) manufacturing of hardened steel automobile parts (e.g. crankshafts, camshafts and injection nozzles). Althaus performed a comparative study on dressing of vitrified bonded CBN grinding wheels, using a diamond cup dresser, to dress a straight profile on wheels for internal grinding [Alth81]. Althaus also mentions the use of a driven diamond form roll in a parallel axis orientation and an non-driven diamond roll with an axis tilted 18 degrees to the grinding wheel axis to create a relative velocity, but gives no experimental results with these set-ups. Satisfactory results are achieved with the cup dresser.

Ishikawa [Ishi91] used a metal bonded diamond grinding wheel of 0.5-1 mm width to dress vitrified bonded CBN wheels. For increasing depth of cut in dressing \( a_{cut} = 1.5-2.5 \mu m \), workpiece surface roughness Ra increased, grinding wheel radial wear increased slightly and power consumption in grinding decreased, the same holds for increasing truing lead and increasing diamond grit size in the dresser. Increasing the speed ratio \( q_d \) from 0.2 to 0.8 shows a comparable effect as the other parameters. The material removal mechanism shifts however more to a crushing behaviour (see
section 3.2.9 below) which results in a more open structure of the grinding wheel surface. Ishikawa tried to investigate the material removal mechanism by studying the wheel surface and fracture mode. It was shown that at higher depth of cut, increased truing lead and increasing diamond grit size there is more macro-fracture of the CBN grains leading to sharper cutting edges.

Warnecke and Spiegel [Warn90] compared a diamond form roll with a dress tool equipped with PCD cutting edges (designated a mill cutter). Both were used on a resin bonded CBN grinding wheel and high $G_d$ ratios were observed for the mill cutter. However due to the low diamond content on the circumference of the tool the effective radial wear of the roll was very large. With the more conventional diamond roll $G_d$ ratios of 1160-2850 were reached, the higher values due to intermediate resetting of the bond material of the grinding wheel with an additional sharpening operation ($\text{Al}_2\text{O}_3$ block sharpening).

Yokogawa and Yokogawa developed a dresser with a rotating diamond disc equipped with large diamonds [Yoko92]. This dresser is shown to perform just as well as a single point diamond dresser, but with very low wear enabling accurate dressing of wide wheels and step profiles. The authors mention a difference in dressing of CBN and conventional wheels: the total dressing amount must be much smaller. This is also brought forward by Tönshoff and Heuer [Töns92] and named touch-dressing [Töns95]: when a CBN grinding wheel is dressed with an amount as large as the average grain size the wheel surface is not open enough to use. Therefore an extra sharpening operation or at least free grinding (see 3.2.2) is needed. The basic idea in touch dressing is that only when a new wheel is used for the first time, additional sharpening is needed, after that the dressing depth should be kept significantly smaller than the chips space which is on average 35% of the average grain diameter according to Tönshoff [Töns95]. During grinding the chip space is then maintained automatically, as in free grinding, but without the need to reduce the material removal rate $Q'_w$. This is achievable on super-abrasive wheels where the wear is small. The high price of the super-abrasives is another argument to use touch-dressing as it minimises tool consumption [Töns92], [Töns94].

Klocke and Schulz studied the wear of the diamond form rolls when dressing vitrified CBN wheels and report $G_d$ values that are between 5000 and 14000 depending on the speed ratio $q_d$; the highest values are reached at $q_d = 0.3$ [Kloc95b], [Schu96].

Dressing of diamond grinding wheels with a rotary diamond tool is described by several authors including [Claa80], [Arde03], [Warn90]. Claassen and Heuven [Claa80] describe the use of metal bonded diamond wheels for profiling radii on resin bonded diamond wheels. The developed tool uses standard metal bonded diamond wheels as form roll, these form rolls were driven at a speed ratio of around $q_d = +0.5$ to 0.6 and reported $G_d$ ratios were in the range of 20-50. Warnecke and Spiegel also performed experiments on resin bonded diamond wheels and found that dressing with a mill cutter leads to $G_d$ ratios of around 150 [Warn90]. Spur and Liebe [Spur95] used a diamond
form roll on a resin bonded diamond wheel and achieved $G_d$ ratios of 10-23 over a wide range of $q_d$ values, it was also shown that an increasing relative velocity leads to higher $G_d$ values. They also compared the cost between profiling with diamond rolls and SiC wheels (see 3.2.7). Indicating that when using diamond rolls, the tool costs amount to 2/3rd of the profiling cost, while in rotary abrasive dressing they are negligible. The total cost for the two processes are, in the given example, comparable. Mancina profiled specially developed diamond and CBN grinding wheels with both resin and metal bonds that are dressed with dedicated metal bonded diamond form rolls; however no results on accuracy and profiling tool wear are provided [Manc81]. Generally galvanic bonded single layer grinding wheels are regarded as not dressable. However touch-dressing is sometimes used on these single layer wheels for truing and to decrease the surface roughness achieved with new grinding wheels (e.g. by Aurich [Auri08], and Cooley and Juchem [Cool91]). In recent years developments for profiling vitrified bonded diamond grinding wheels are seen. The brittle behaviour of the bond combined with its hardness and open structure contribute to its success. Shih did a comparative study on dressing of grinding wheels for circular grinding of Zirconia ($\text{ZrO}_2$) parts [Shih00]. In this study a diamond grinding wheel as well as a CBN and a SiC wheel, all with a vitrified bond system were used. For dressing the straight profiles a rotary diamond dresser was used. Depth of cut $a_{cut}$ as small as 0.8 µm was used on the diamond wheel. In this experiment the overlap could not be varied and is not specified. A wide range of speed ratios $q_d$ was investigated. However the effect on the grinding output (tangential grinding forces, workpiece roughness and roundness) was small.

Ardelt and Meyer [Arde03] have successfully used diamond form rolls for profiling vitrified diamond wheels. When diamond form rolls are used for grinding wheels with softer abrasives the wear of the roll is neglected, however when used on diamond grinding wheels this cannot longer be assumed. The approach of Ardelt and Meyer is therefore different: the wear of the roller is accepted and the effects are controlled. The used diamond roll consists of large diamonds (average grit size 1000 µm) in a sintered bond, the width of the form roll used is 0.9 to 1.2 mm [Arde04]. The basic idea behind this dressing process is that when the same contour is made over and over again a steady state wear profile will build on the form roll. The wear of the form roll will therefore only be seen as a deviation of the radii of the grinding wheel and the dress roll. This radius deviation has to be compensated for. In Figure 3-5, taken from [Arde03] the development of such a wear profile is demonstrated for a symmetrical shoulder profile. Starting with a round profile on the dress roll, after the 40th dressing pass no variation of the profile is seen till the end of the wheel life. This implies that the wheel profile is created very accurately (basically limited by the system stiffness, accuracy of the NC and the profilability of the grinding wheel) the authors claim a profile accuracy of +/- 3 µm. The limit of the process lies in the achievable contour details; fine profiles as needed e.g. for making tapping and threading tools cannot be made, also small inner radii on the grinding wheel are limited.
Getting the profile right the first time is also difficult: the tool has to wear in and after that the toolpath has to be adapted to counter-effect the wear of the roller. This continues in an iterative way until the wear profile is stationary and the result is satisfying. From that moment on automated grinding and profiling is feasible, as long as the radial wear is taken into account. Parameters used in this process are: $q_d=+0.3$ to 0.8, $U_d = 2-3$ for roughing and 4-6 for finishing [Arde04] although values as high as 35 are also documented due to wear [Arde03], depth of cut $a_{cl} = 3-5$ µm. $G_d$ ratios are not mentioned in the article but research by Derkx has shown values around $G_d=100$ on a D46 C100 vitrified wheel [Derk05] (see section 9.3 for more information). Recently a dressable resin bond system was introduced [Mack07] for this profiling method.

Reflecting on these researches the major difference between dressing of vitrified and resin bonded diamond wheels seems to be the speed ratio $q_d$. For the resin wheels negative $q_d$ values are used (counter directional dressing) while for vitrified wheels positive values are used (unidirectional). This can be understood from the fact that the material removal mechanism is different: with the brittle vitrified bond system brittle fracture of the bond system is the most efficient removal mechanism (see also section 3.2.9 on crushing below).

**3.2.9 Crush dressing**

Instead of making use of an abrasive material removal mechanism as in rotary diamond dressing, the same tools can be used in a so-called crushing process. In crushing the grains of the grinding wheel are loaded by the dressing tool with only a normal force. This normal force introduces
stresses in the bond material supporting the grain. If the bond material is brittle and the stresses are sufficiently high the bond bridges will fracture and the total grain is dislodged and can drop out of the grinding wheel, this is illustrated in Figure 3-6. In this way the grinding wheel can be profiled. This process has since long been used to profile conventional grinding wheels, as already in 1943 a dissertation on the subject was published by Rauschnabel [Raus43]. To assure that only a normal force is transferred the dressing tool and the grinding wheel should have the same circumferential speed (i.e. \( q_d = 1 \)), the normal force is then applied by moving the two bodies radially towards each other. The demand for brittle behaviour of the bond limits the application to vitrified and a special class of (brittle) bronze bond systems [Barn89a].

![Figure 3-6: Crushing mechanism [Hess03]](image)

**Profile crushing**

In profile crushing the needed profile is contained in the profile roll, as in rotary diamond profile dressing, see Figure 3-7a. The speed ratio of \( q_d = 1 \) is generally achieved by driving only one body and keeping the other free running, relying on friction to synchronize the circumferential speeds.

![Figure 3-7: Profile and form crush dressing principles](image)
The used dressing speed \( v_{sd} \) is about an order of magnitude lower than the speed in grinding \( v_{g} \). The specific dressing forces in crushing are higher than in rotary diamond dressing and normal forces of up to \( F'_{nd} = 100 \) N/mm contact width are reported [Geis80].

Althaus compared crushing of CBN grinding wheels with diamond cup dressing on an internal grinding machine [Alth81]. In the experiments a speed of \( v_{sd} = 3 \) m/s and a feed of \( f_{rd} = 0.13 \) µm/rev are used. The author reports high initial wear directly after crushing, leading to reduced G-ratios. Finer grained wheels led to better results both in G-ratio and surface quality. Compared to cup-dressing the workpiece roughness is much higher and the influence of the grain size is more pronounced. The forces in grinding after crushing are significantly lower and more constant, indicating that the grinding wheel topography after crushing is closer to the quasi-static topography. Spark-out in crushing showed an insignificant influence on roughness and normal forces. The high forces in crushing and the low system stiffness in internal grinding (10 N/µm) made it difficult to remove run-out. Furthermore the fact that crushing is done at low speed results, even when run-out is removed at crushing speed, to a run-out at grinding speed due to the different dynamic behaviour of the machine at another speed. The remaining run-out limits the application of crushing in internal grinding. Geisweid noticed the same issue and stresses the need for very accurate static balancing of the grinding wheel [Geis80]. Due to the increased loop stiffness of the system used by Geisweid static balancing was sufficient to avoid problems during grinding.

Barnard used a hydraulically powered device to drive the crush roll at circumferential speeds ranging from 0.3-1 m/s and stresses the need for copious application of (high pressure) grinding fluid to clean the surface from dressing debris [Barn89a]. Barnard also documented a set of case histories, indicating achievable profile radii down to 0.07 mm, profile angles as small as 6 degrees to the vertical and profile accuracies of +/- 0.03 mm [Barn89b]. The achievable profile radius is limited to about 2 times the average grain radius [Töns79]. Geisweid compared a vitrified and crushable bronze bonded wheel at a constant specific crushing normal force of \( F'_{nd} = 30 \) N/mm [Geis80]. The bronze bonded wheel shows initially material removal, but after about \( a_{delt} = 40 \) µm the removal stops. The grinding wheel surface is closed and shiny due to the binder and graphite particles that are compacted into the wheel surface. Material removal can be started again by increasing the crushing force but this leads to damage of the wheel. The vitrified grinding wheel on the contrary showed a constant material removal for a given crushing normal force. This can be achieved for the bronze bonded wheel when abrasive sharpening with a vitrified Al2O3 block is applied simultaneously. This is also confirmed by [Schw82]. Both [Töns79] and [Geis80] mention the effect of relative speed between grinding wheel and form roll due to radii difference along a profile, as illustrated in Figure 3-8. Due to these radius variations the relative speed, \( v_{rel} \), varies along the profile resulting in uneven wear and therefore loss of profile accuracy.
Increasing the crushing speed $v_{sd}$ leads to increased wear and both Geisweid and Barnard recommend keeping $v_{sd}$ below 1 m/s to keep wear within acceptable limits. Reduction of profiling time is better achieved by increasing the crushing depth $a_{wd}$. Reduction of contact time also reduces form roll wear, even when the crushing forces are higher due to the increased depth of cut [Geis80].

Form crush dressing

The major problem in rotary diamond profile dressing of diamond grinding wheels is the excessive wear of the form roll, limiting its application to straight and simple profiles [Shih98]. The limited wear of the profile crushing rolls combined with the flexibility of form dressing results in crushing with a form roll and is called form crushing, also known as point crushing or NC crushing and shown in Figure 3-7b. The first documentation on this process is in a patent laid down by Kaiser [Kais96]. Harbs used hardened steel and tungsten carbide form rolls to profile a vitrified diamond grinding wheel; based on these results the use of diamond form rolls is suggested to reduce wear. Furthermore the need for an accurate drive system for the form roll was formulated together with the possibility to regrind form rolls on the machine [Harb97]. Further research into the form crushing process was done at the university of Hannover in cooperation with a grinding wheel manufacturer and a dressing tool supplier, resulting in numerous publications [Denn99a], [Denn99b], [Töns01], [Töns02], [Denn02], [Denk04], [Hess06] and a dissertation on the subject by Hessel [Hess03]. The strength of form crush dressing is a reduction of form roll wear, which is roughly a factor 10 lower as compared to rotary diamond truing, based on the work of Hessel [Hess03] and Derkx [Derk05]. Shih also reported the highest $G_d$ ratios near the crush dressing regime: $G_d$ of 300 at $q_d=1.2$, a value of $q_d=1$ was not employed, Hessel documented $G_d$ ratios of up to 1200 with a dedicated point crush dressing system restricting $q_d$ to be 1 [Hess03]. The information in the section below is based on the work of Hessel [Hess03].

Due to the small contact area of the profiling tool the tool has to be traversed along the grinding wheel profile. This would result in rather long profiling times. Therefore the crushing speed is
chosen significantly higher than in profile crushing, values from \( v_{sd} = 10-20 \text{ m/s} \) are reported, to reduce the profiling time. Hessel also showed that due to the decreasing contact surface and increasing speed the form roll and grinding wheel have to be driven and synchronized to achieve an overlap ratio of \( q_d = 1 \) and to avoid slip every time contact between the two bodies is established. The wear of an un-driven roll was about 4-12 times higher, even while making use of a more wear resistant type of form roll. Hessel used form rolls with a diameter \( d_r \) of 100 mm, top radius \( R_{top} \) of 200 \( \mu \text{m} \) and top angle of 50\(^\circ\). 4 different form rolls where studied, all containing diamond. Three rolls contained large diamond particles manually arranged along the circumference and embedded in a hard bond. One roll contained a polycrystalline, solid, continuous diamond layer created in a CVD process. The latter roll showed the lowest wear. From the other diamonds the polycrystalline diamonds (PCD) made of diamond powder bonded with cobalt showed the highest wear.

Research was performed into the influence of the crushing depth \( a_{ed} \), grinding wheel properties, overlap ratio \( U_d \) and crushing speed \( v_{sd} \) on the crushing and grinding forces, grinding wheel topography and form roll wear. Only vitrified bond grinding wheels where studied. The results of this work are summarized in Figure 3-9. Increasing the grain size or hardness of the binder increases the specific crushing forces thereby reducing the \( G_d \)-ratios and increasing the roughness of the grinding wheel surface. Increasing the crushing depth \( a_{ed} \) does not affect the wear ratio of the form roll or the roughness of the wheel surface; however the specific crushing normal force increases.

\[
\begin{array}{|c|c|c|}
\hline
\text{Wear ratio in form crushing } G_d & \text{Specific dressing normal force } F'_{nd} & \text{Wheel surface roughness} \\
\hline
\text{System parameters} & & \\
\text{Increasing grinding wheel grain size} & \rightarrow & \rightarrow \\
\text{Increasing grinding wheel binder hardness} & \rightarrow & \rightarrow \\
\text{Control parameters} & & \\
\text{Increasing crushing depth } a_{ed} & \rightarrow & \rightarrow \\
\text{Increasing overlap ratio } U_d & \rightarrow & \rightarrow \\
\text{Increasing crushing speed } v_{sd} & \rightarrow & \rightarrow \\
\hline
\end{array}
\]

\( = \) Not driven roller

Figure 3-9: Relations in form crushing [Hess03]
Increasing the overlap ratio $U_d$ in the range of 1-4 leads to lower wear ratios due to the increased contact time between the two bodies, reduced specific crushing forces because the material removed per time unit is smaller and slightly lower roughness of the grinding wheel surface. Above $U_d = 8$ no influence was observed. Increasing the cutting speed $v_{sd}$ has a positive influence on the form roll wear, reduces the crushing normal forces and has no significant influence on the grinding wheel surface roughness.

The grinding wheel surface after crushing shows large chipspace compared to SiC rotary abrasive dressing, making an additional sharpening operation unnecessary. The topography after crushing is close to the quasi-static topography of the grinding wheel during use, leading to a constant process behavior which is advantageous for automation of a grinding process and no need for a sharpening operation.

A profile to grind metric threads with a height of 800 µm and a (external) top radius of 200 µm was used to investigate the performance of a profiled grinding wheel. The results show that directly after profiling the wear of the grinding wheel during grinding is high. After this initial wear the wear stabilizes at a more or less constant rate. The initial wear showed to be very dependent on the grain size: larger grain size leads to higher initial wear. Grain sizes used in this research included D12-22, D30-40 and D54. A grinding wheel with D3-4 grain size was also used. The profile was created very accurately into this grinding wheel, but the wheel failed during grinding: after a few mm of grinding the complete profile was worn down. The grinding wheel was loaded with hardmetal leading to increased forces and destruction of the grinding layer. For the other grain sizes an increase in the depth of cut $a_{sd}$ invoked an increase in the initial wear which can be explained by the increased damage to the grinding wheel surface by the higher process forces $F_{nd}$. This influence gets smaller for larger average grain size of the grinding wheel, indicating the importance of relating the crushing depth to the grain size. The feed speed along the profile $v_{fad}$ showed no significant influence. For the D3-6 case the relative crushing depth might simply have been too large, leading to compacting of the grinding wheel surface. Also the influence of vibrations and run-out becomes, relative to the grain size, larger.

The reduced wear at increased crushing speed seems to contradict the results published on profile crushing by Geisweid [Geis80]. This can be explained by the fact that the systems used in profile crushing rely solely on friction to drive the second body. This leads on the one hand to increased acceleration slip and on the other hand to increased slip at higher speeds as the friction torque of the non-driven body increases. This is indeed confirmed by the experiments of Hessel with a non-driven roll. The increased crushing speeds could however not be exploited fully because at the higher speeds the initial wear of the grinding wheel was larger, indicating increased damage to the grinding wheel structure.
3.3 Chemical and thermal dressing

In section 3.2 mechanical based dressing methods were discussed. In this section dressing methods making use of thermal and chemical effects are introduced.

3.3.1 Electrochemical dressing

Grinding wheels having a conductive bond can be sharpened by electrolytically dissolving the metal bond material. This effect was known since the late 50’s of the last century but the most well known and established process is known as electrolytic in-process dressing (ELID) and was presented in its refined form by Ohmori [Ohmo90], [Ohmo92]. In Figure 3-10a the system is shown: during grinding an electrode is located close (0.1 mm) to the grinding wheel surface. An electrolyte (specially adapted grinding fluid) is flooded between the grinding wheel and the electrode, which are connected to the poles of a pulsed DC power supply.

![ELID system schematic](image)

*Figure 3-10: ELID system schematic as proposed by Ohmori [Ohmo92]*

Due to the potential between electrode and grinding wheel the grinding wheel bond is electrolytically dissolved forming an (hydr-)oxide layer at the wheel surface, see Figure 3-11. This layer has isolating properties which slows the process down. During grinding the soft oxide layer is removed and the ELID process continues. In this way the ELID process is self-regulating.

![Electrolytic dressing principle](image)

*Figure 3-11: Electrolytic dressing principle as proposed by Ohmori [Ohmo92]*
The main application of ELID has been the grinding of hard and brittle materials like silicon wafers [Ohmo90], optical glasses [Ball91] ceramics [Ball91], [Wije97] and tungsten carbide based hardmetal [Wije96] with extremely low surface finish. This is possible due to the use of very small grit sizes, e.g. the use of 8000 mesh, having an average grit size of 0.5-3 µm is not uncommon. Surface finishes achieved are mostly below 10 nm Ra. Stephenson used the ELID process to dress ultra fine grained CBN grinding wheels to produce optical surface quality (Ra < 10 nm) on hardened steel [Step01]. The advantages of grinding over polishing are that in grinding the form tolerance is better controllable and the material removal rate is significantly higher. The use of electro chemical dressing is however not limited to ultra-precision grinding with ultra-fine grained wheels as is shown by Kramer who built a complete system employing electro chemical dressing and used it to grind cermets, PCBN and PKD tools [Kram99]. The main difference compared to ELID is that much higher grain protrusion can be achieved: up to 100% of the average grain diameter, while in ELID grinding this will be about 50-60%.

As can be seen in Figure 3-10 the grinding wheel has to be connected to the power source. This has the disadvantage that a wearing and often unreliable slip ring has to be used, and that the spindle has to be electrically isolated from the rest of the machine. In 1991, Suzuki proposed an electro chemical dressing (ECD) method with a twin electrode that avoids using a wire brush and employs an alternating current that can be created in a very simple and cost effective way. This method was proven to provide effective sharpening, its main advantage being its simplicity [Suzu91].

3.3.2 (W)EDM dressing

Grinding wheels with a conductive bond system can also be profiled with electro discharge machining. EDM makes use of a conductive tool and an electrolyte: a sufficiently high voltage is applied between the tool and the grinding wheels to make sparks travel from tool to grinding wheel. The heat generated by the sparks impacting on the grinding wheel surface leads to melting and evaporation and thereby to removal of material. Profiles can be created by die-sinking an electrode containing the negative of the demanded profile [Suzu87], into the grinding wheel. Also possible is the use of wire-EDM in which the electrode consists of a wire that is continuously renewed [Suzu87], [Rhon01]. The latter is convenient as the tool in EDM is not completely free of wear. The main drawback of WEDM is that the material removal rate is small due to the small effective area. Wires down to 0.05 mm are used in WEDM. Rhoney reported achievable external profile radii of 118 µm and 82 µm internal radii with a 0.254 mm diameter wire. Profile accuracies of 2-6 µm are claimed [Rhon01]. With die sinking Wang reports material removal rates of 1-4 µm/min on a fine grain metal bond diamond wheel [Wang96]. Ortega mentions sharpening times of 10-40 minutes and comparable times (at different EDM settings) to remove initial run-out [Orte04]. This relatively low material removal rate is one of the drawbacks of EDM profiling. Another
disadvantage is found in the fact that diamond is not conductive, therefore only the bond material is eroded and the diamond grains will drop out when all the supporting bond material is removed. The gap distance between the electrode and the grinding wheel should therefore be larger than the average grain diameter; otherwise the grains will come into contact with the electrode (generally graphite, copper or tungsten) and compromise contour accuracy. Suzuki noticed this effect and employed electrically conductive diamond particles that could be eroded, to resolve the problem. Furthermore Suzuki shows that the tool wear can be strongly reduced by making use of conductive diamond as an electrode material [Suzu04] [Suzu07].

3.3.3 Electro contact discharge dressing

The advantage of the twin electrode ECD method of Suzuki [Suzu91] is also used in electro contact discharge dressing (ECDD). In this method the material removal principle is comparable to EDM dressing, only the two-pole electrode is lightly ground. A spark will be generated when the chip from the electrode approaches the conductive grinding wheel bond. The heat generated by the evaporating chip leads to thermal bond erosion, see Figure 3-12.

Figure 3-12: Principle of electro contact discharge dressing after Tönshoff

This method is simple and cost effective and proved to have a high truing efficiency and grain protrusion [Tama94] and less grain wear compared to abrasive dressing [Töns00]. Especially with the rotary twin electrode suggested by Tamaki very low run-out values (< 1 µm) can be achieved [Tama92], [Tama94]. Friemuth has successfully applied ECDD for sharpening diamond wheels for grinding of advanced tool material (cermets, ceramics, hardmetal, PCD) [Frie98] and metal bonded CBN wheels [Frie00]. All authors report significantly reduced grinding forces due to the high grain protrusion and sharp cutting edges compared to abrasive dressing. Tamaki also used a special conductive resin bonded CBN wheel with ECDD and reports reduced wheel wear compared to abrasive dressing [Tama03]. ECDD is not used to profile grinding wheels.
3.3.4 ECDM

Oguma combined EDM and ECM dressing methods to use both the sharpening effect of ECM dressing and the profiling ability of EDM based processes [Ogum99]. However both processes make use of different equipment and are therefore difficult to integrate on one machine. The principle of material removal by combined spark erosion and chemical dissolution is published by McGeough and Khairy who indicate that the primary material removal mechanism is spark erosion, assisted by chemical dissolution [McGe83], [Khai90]. Schöpf employed this principle in electro chemical discharge machining (ECDM) of metal bonded diamond grinding wheels to achieve wheel run-out below +/- 1 µm and very high grain protrusion of 75-100 % of the grain diameter. After installation on a centreless grinder lower roughness and lower forces were observed resulting in improved roundness [Schö01].

3.3.5 Laser (assisted) dressing

The first reference to the use of lasers in dressing of conventional grinding wheels is made by Ramesh Babu in 1986 [Rame95]. The use of lasers as a non-contact tool to dress super-abrasive grinding wheels is suggested by Westkämper [West95]. In his work the sharpening of a resin bonded CBN wheel is demonstrated. Hosokawa sharpened a bronze bonded diamond wheel with a laser oriented normal to the grinding wheel surface and added an air-jet to blow away the molten bond material and avoid resolidification on the wheel surface [Hoso06]. The material removal mechanism is based on vaporizing and melting of the metal bond material or decomposition of the resin bond, by the heat input from laser irradiation. Kang used a laser in a tangential orientation to true diamond grinding wheels. The diamonds are removed when the bond material around them is molten and removed [Kang01]. Run-out values of around 10 µm are reported which are not sufficient for precision grinding.

A different approach is taken by Zhang who uses a laser together with a single point diamond dresser to true vitrified CBN wheels. Principally the bond material is preheated facilitating the material removal by the single point diamond, thereby decreasing the wear of this stationary dresser. High truing efficiency (material removal rate) is reported, the achieved run-out values of 5 µm are comparable to the values achieved with only single point diamond dressing on the same set-up [Zhan02] [Zhan03]. Principally this method can be used to profile super-abrasive wheels.

3.4 Conclusion on super-abrasive wheel dressing

As the sections above illustrated there are numerous ways to dress super-abrasive grinding wheels. All methods have their disadvantages and limitations. So far no method is available that can create complex and detailed profiles on diamond grinding wheels with high accuracy and high flexibility. EDM dressing is a promising method to profile grinding wheels, however wire-EDM is flexible but very slow, while die-sinking is faster but not very flexible. Furthermore electrode wear is still an
issue limiting accuracy and the equipment is difficult to install on standard grinding machines due to parasitic currents in the machine that can ruin bearings and slideways and incompatibility of the electrolytic fluid. Rotary diamond dressing and form crushing are the most flexible and accurate profiling methods, the latter being more capable of generating complex profiles with intricate details. Wear of the form roll is the biggest challenge as it directly affects the accuracy on complex profiles.
4 Project definition

4.1 Aim of the investigations

As motivated in the preceding chapter profiling of diamond grinding wheels is a challenge that is not generally solved at this moment. Especially the flexibility, accuracy and achievable profile complexity of available profiling methods is limited. Some of the methods seem to be hindered not directly by the employed material removal mechanism but also by the limitations of the equipment used.

In the previous chapter the profiling process form crushing was identified to be the most promising process based on its potential flexibility and accuracy but also because form crushing can be integrated on a grinding machine without difficulties. Limited research on this process is available and the results published suggest that the full potential of this method is not yet uncovered. To unleash this potential several aspects need attention:

System design: as in every manufacturing operation the equipment used affects the process output. The equipment used in earlier research have been adaptations of existing dressing systems. To maximize the performance of the form crushing process a set-up has to be developed specifically dedicated for this purpose.

Achievable accuracy: accuracy is determined on the one hand by the movement of the tool and therefore a limit of the system. On the other hand the actual profiling process, defined by the used grinding wheel and profiling tool will have an influence. This influence is to be researched to determine the limits of the process.

System flexibility: based on the trends in manufacturing towards product diversification and smaller batch sizes the ability to efficiently generate a wide variety of profiles is considered important in this project.

Process flexibility: all profiling systems have limitations in their application. During this research the profiling process should be explored to determine to what extent the application of the profiling process limits its applicability. In this context it is vital to realize that profiling is done in support of an actual grinding process. Ideally the profiling process should not put any restrictions on the following grinding operation. In practice profiling operations have a limited set of grinding wheel types that can be used and influence the grinding performance of the grinding wheels, thereby limiting the end-user to choose the best wheel for the grinding task at hand. Earlier research
showed for example difficulties when profiling very fine grained grinding wheels. Research is needed to investigate if this is a fundamental limit or that the observed difficulties are caused by either the limitations of the equipment or the used grinding wheel. Research to formulate the limits of the process has to be done.

The aim of this research can therefore be summarized as:

*It is the aim of this research to develop a flexible and high accuracy profiling system for diamond grinding wheels.*

### 4.2 Approach and outline of the thesis

With a profiling system the equipment as well as the process is indicated. Therefore, to achieve this goal, an integral approach is followed: the research includes on the one hand development of a dedicated machine tool and control which will be integrated on an existing grinding machine, and on the other hand profiling process development and optimization. Because of the strong interaction between machine tool design and process performance [Töns98a] this approach is necessary to achieve maximum performance. As a first step the demands on the profiling device are defined. These demands are based on the available research and demands from industry and form the basis for the development of the profiling system, which is the subject of chapter 6. A challenge specific to form crushing is the active synchronization of the form roll and grinding wheel speed to achieve a speed ratio of exactly $q_d = 1$. This subject is therefore covered separately in chapter 7.

Chapters 8, 9 and 10 deal with the process development. Chapter 8 documents the experiments that support the process design: the form roll composition, on-machine regrindability and regrinding cost are considered, resulting in a complete profiling process. This process is then the basis for the experiments in chapter 9 where the factors influencing the profiling time and accuracy are studied. These include the grinding wheel composition and crushing process parameters, their effect on the grinding behavior is also studied. The insight gained with these experiments is put into practice in chapter 10 where several case studies are documented, showing the capability of the developed system. The work is concluded in chapter 11 with conclusions and recommendations for future research and application in industry. The used experimental and measurement equipment and measuring methods are covered separately in chapter 5.
5 Experimental and measurement equipment

The equipment used for the experiments and the measurement equipment and procedures are described in this chapter.

5.1 Experimental equipment

5.1.1 Grinding machine

The experiments are performed on a 3-axis surface grinding machine shown in Figure 5-1. The machine was equipped with a direct measuring system on all axes with a resolution of 0.1 µm. The main spindle is of a direct drive type with 16 kW power at a maximum of 8000 rpm. The machine has recirculating ball bearing guides on all axes. Peripheral grinding wheels with a diameter ranging from \( d_s = 200 ... 400 \) mm can be used. A maximum width of the wheel of \( b_s = 80 \) mm can be mounted. An automatic balancing system is available to balance the grinding wheel and reduce wheel run-out. The machine is controlled by a numerical control (Siemens 840D). The static loop stiffness of the machine was measured in Y-direction and found to be 20 N/µm.

Some machine properties are summarized in Table 5-1.

Figure 5-1: Surface grinder Blohm Planomat [NNBloh]

For research on profiling of grinding wheels the repeatability of the machine is most important. The contouring repeatability was found to be within 1 µm. This was tested with a two-axis glass scale (type Heidenhain KGM 182). However this was only valid if the contour was followed in the same direction. A result of this test in the Y-Z plane is shown in Figure 5-2 below. Shown is the result of a
circle test: a circle of 50 mm radius is followed by the machine. This was done in clockwise (CW) and counterclockwise (CCW) direction and at two different speeds. In the figure the deviation of the ideal circle is plotted. Two problems in the contouring performance are directly seen:

-1- The CCW contour lies within the CW contour. The deviation is at the largest point 3 µm

-2- The circle is elliptic

The elliptic profile is caused by the fact that the mechanical axis where not square to each other. Even though this problem does not affect the repeatability it was recognized and corrected.

The dependency on the motion direction could not be resolved completely, as it finds it origin in the machine tool design, but was reduced to below 2 µm. The consequences of this defect will be dealt with in chapter 10.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>Planomat 612</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive type</td>
<td>Electro-mechanical w. recirculating ball screws</td>
<td>Guideway type</td>
</tr>
<tr>
<td>Working range</td>
<td>X: 1200 mm</td>
<td>Feed rate</td>
</tr>
<tr>
<td></td>
<td>Y: 550 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z: 600 mm</td>
<td></td>
</tr>
<tr>
<td>Machine loop stiffness C_{stiff} (in Y-direction)</td>
<td>20 N/µm (measured)</td>
<td>Repeatability</td>
</tr>
<tr>
<td>Control</td>
<td>Siemens 840D</td>
<td>Resolution</td>
</tr>
<tr>
<td>Wheel diameter</td>
<td>d_{w} = 200...400 mm</td>
<td>Coolant system</td>
</tr>
<tr>
<td>Wheel width</td>
<td>b_{w} = 30...80 mm</td>
<td>Main spindle</td>
</tr>
<tr>
<td>Wheel bore</td>
<td>127 mm</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-1: Properties of the used surface grinder
5.1.2 Small wheel adapter

To enable the use of smaller grinding wheels an add-on device is available. This device contains an axis that can take grinding wheels in the diameter range $d_s = 50 \text{ - } 100 \text{ mm}$. The small wheel adapter is bolted to the main spindle head and driven via a belt drive by the main spindle. The addition of this device reduces the loop stiffness of the machine, measured in Y-direction, to 7 N/µm.
5.1.3 Grindin g fluid
Use is made of a water-based soluble oil as grinding fluid. Type Cimtech A31 fluid produced by Cimcool was used at a concentration of 4%. The fluid is prepared with demineralized water. Replenishments were also done with demineralized water to avoid mineral build-up that would affect the performance of the fluid. An additive was used to neutralize Cobalt particles that are released during grinding of tungsten carbide based hardmetals. Properties of the fluid used are given in Table 5-2 below.

<table>
<thead>
<tr>
<th>Manufacturer</th>
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</thead>
<tbody>
<tr>
<td>Type</td>
<td>Cimtech A31</td>
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<tr>
<td>Class</td>
<td>Water-soluble synthetic</td>
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<tr>
<td>Viscosity</td>
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<tr>
<td>Concentration</td>
<td>4 %</td>
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<tr>
<td>Additive</td>
<td>Cimplus T4005</td>
</tr>
</tbody>
</table>

Table 5-2: Properties of grinding fluid

5.1.4 Workpiece material
Unless stated otherwise tungsten carbide based hardmetal is used for the experiments in this work with the specification as provided in Table 5-3.

<table>
<thead>
<tr>
<th>Material</th>
<th>Tungsten carbide based hardmetal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
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</tr>
<tr>
<td>Product</td>
<td>MG18</td>
</tr>
<tr>
<td>ISO code</td>
<td>K20-40</td>
</tr>
<tr>
<td>Composition</td>
<td>10% Cobalt binder</td>
</tr>
<tr>
<td>Grain size</td>
<td>0.5-0.8 µm</td>
</tr>
<tr>
<td>Hardness</td>
<td>1660HV/30</td>
</tr>
<tr>
<td>Transverse rupture strength</td>
<td>3700 MPa</td>
</tr>
<tr>
<td>Fracture toughness KIC</td>
<td>9.4 MPa·m¹/²</td>
</tr>
</tbody>
</table>

Table 5-3: Properties of workpiece material

5.1.5 Crush truer
A simple crushing device is used to remove initial run-out after mounting a vitrified diamond grinding wheel. The device consists of a CVD diamond disc with a diameter of 57 mm and a width of 500 µm. The disc is supported by two angular contact ball bearings that are held in a steel frame. The device can easily be mounted on the (magnetic) worktable of a grinding machine or the installed force measuring platform (see 5.2.3). The device is manufactured by Dr. Kaiser
Diamantwerkzeuge GmbH and shown in Figure 5-4. Further discussion of this device can be found in section 6.1.

5.1.6 Form crushing rolls

The form crushing roll is the actual tool used in the form crush profiling process. Form rolls are available in many shapes and sizes. The most versatile and a commonly used shape is a roll with a symmetrical top angle and a defined top radius, as sketched in Figure 5-5.

This type of roll can be geometrically defined by its outer diameter $d_r$, top angle $\theta_{top}$ and top radius $R_{top}$. In most cases the form roll contact area is in some way reinforced with a wear material. Diamond is the most common material and comes in many types, shapes and qualities. For form crush dressing the use of CVD-diamond (chemical vapour deposited) or PCD (poly crystalline diamond) bars (e.g. of size 0.8 x 0.8 x 5 mm) is most common. If not specified otherwise the experiments are performed with a form roll with $d_r = 120$ mm, $\theta_{top} = 40^\circ$ and $R_{top} = 100 \mu$m. CVD diamond wear parts are used on the circumference as shown in Figure 5-5. The used form roll was
5.1.7 Data acquisition system

To measure and analyze the forces and AE signals and for the implementation of the control system developed in chapter 7 a desktop computer with a data acquisition system is employed. The used system has both analog and digital in- and outputs. The analog inputs can be sampled with a speed up to 250 kS/s. More details on the used data acquisition card can be found in Table 5-4 below.

<table>
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</tr>
</thead>
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<td>Analog in</td>
<td>16 channels</td>
<td>16 bit resolution</td>
<td>Max 250 kS/s (1 channel)</td>
</tr>
<tr>
<td>Analog out</td>
<td>2 channels</td>
<td>16 bit resolution</td>
<td>833 kS/s</td>
</tr>
<tr>
<td>Digital I/O</td>
<td>24 channels</td>
<td>-</td>
<td>1 MHz</td>
</tr>
<tr>
<td>Counter/timer</td>
<td>2</td>
<td>32 bit</td>
<td>80 MHz</td>
</tr>
</tbody>
</table>

*Table 5-4: Specification of data acquisition system*

The programs for the control of the card where developed using a graphical programming software package: National Instruments Labview 7.1.

5.2 Measurement equipment

5.2.1 Stylus contact profilometer

To determine the surface roughness and profile accuracy measurements were performed on a Rank Taylor Hobson type Form Talysurf Series 120L stylus instrument Figure 5-6, left. The stylus instrument is a tactile device that measures by contacting the surface with a conical diamond tip with a radius of 2 µm. The resolution of the gauge is 16 nm. For the profile measurements a tip with a reduced top angle of 40 degrees was available. Roughness measurements where performed with a cut-off of \( \lambda_c = 0.8 \) mm, 5 cut-offs measuring length and a bandwidth of 1:300, as is the ISO standard. In some cases the sample was not large enough to use 5 cut-offs, in that case the maximum available measuring length is used.

5.2.2 White light interferometer and confocal microscopy

To qualitatively study surfaces use is made of a Veeco Wyko NT3300 white light interferometer (Figure 5-6, right). This is an optical, non-contact measuring method. The vertical resolution of this device is 0.1 µm. Pictures of grinding wheel and form roll surfaces were taken using a confocal microscope. Confocal microscopy has advantages over interferometry when the sample contains steep surfaces. In Figure 5-7 the used Sensofar PLµ 2300 is shown. With the used 50x objective repeatability is 4 nm, maximum slope 42° and the spatial sampling distance 0.33 µm.
5.2.3 Grding force measurement

For the determination of the forces during grinding the grinding machine was equipped with a force measuring platform (dynamometer). The platform contains 4 piezocapacitive sensors, having high sensitivity and a large measuring range as the main advantages. The platform used was of type 9257B manufactured by Kistler AG enabling measurement in 3 orthogonal directions. The main properties are given in Table 5-5. The grinding forces where for all experiments evaluated by taking the average over 2 seconds around the moment specified. This was done to eliminate the influence of noise and dynamics on the measurement. The measurements where performed by using a (analog) 100 Hz low pass filter and a sample speed of $f_s = 1 \text{ kHz}$. 
<table>
<thead>
<tr>
<th>Type</th>
<th>9257B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Kistler AG</td>
</tr>
<tr>
<td>Measurement range</td>
<td>+/- 5 kN</td>
</tr>
</tbody>
</table>
| Sensitivity *        | $s_x$, $s_y$ 7.5 pC/N  
|                      | $s_z$ 3.7 pC/N |
| Rrigidity            | $c_x$, $c_y$ > 1 kN / µm  
|                      | $c_z$ > 2 kN / µm |
| Natural frequency ** | $f_{nx}$, $f_{ny}$ 2300 Hz  
|                      | $f_{nz}$ 3500 Hz |

* Resolution dependent on amplifier and system properties and settings
** Natural frequency of the platform only, in practice mass loading has to be taken into account, reducing system natural frequency

Table 5-5: Properties of 3-component dynamometer

5.2.4 Grinding wheel wear measurement

Measurement of grinding wheel wear was done by grinding a workpiece that is smaller than the grinding wheel (Figure 5-8a). In this way a wear profile is created in the wheel. Following this profile is copied into a very soft specimen by grinding the specimen with the full width of the grinding wheel. The unused surfaces of the grinding wheel now function as reference surfaces and the wear profile appears as a stepped profile in the graphite specimen (Figure 5-8b). Subsequently a contact stylus measuring machine is used to determine the profile of the specimen (Figure 5-8c). Especially for small amounts of wear (below several µm) the roughness of the specimen complicates the evaluation. Therefore a least squares (LS) approximation of the two reference surfaces and the wear section was used to determine step height (Figure 5-8d). This lead to reliable and repeatable results even for small values of wear.
Figure 5-8: Measurement of grinding wheel wear
6 Development of the profiling device

This chapter deals with the development of the form crush profiling device. It gives insight in the major device requirements and design decisions and an overview of the overall design process. Furthermore the realized design is evaluated. In 6.1 an evaluation of commercially available form crushing devices and their application field is given, leading to a set of shortcomings and points of improvement. Following on this evaluation the use of the device that is to be developed is described. Based on this a user requirements list is formulated. In 6.2 the user requirements are translated into more concrete design requirements. The next step, described in section 6.3, involves the materialization of the identified functions of the device. At this stage possible design solutions for every function are developed and evaluated. Based on this evaluation a principal system design is presented and further detailed in section 6.4. Finally in 6.5 the realized design is evaluated on some critical issues and improvements are proposed.

6.1 User requirements on a form crush profiling device

An ideal profiling system should not be limited in the achievable profiles, cost no machining time for profiling, have a good accuracy and should not wear. Furthermore such a system should be able to work autonomously (no operator intervention). Ideally this should be achieved at minimal cost. In reality the situation is different. Two commercially available form crushing devices and their use are discussed in section 6.1.1 below. This can be considered as the present state of the art in form crushing devices. Subsequently a method to use form crushing flexibly and with high accuracy is proposed (6.1.2). Based on this a set of user requirements is formulated in 6.1.3.

6.1.1 Existing form crushing devices and their use

On the market two dedicated systems are available for form crush dressing. Apart from these dedicated systems it is possible to use form crush dressing in combination with common form dressing spindles. Although form crushing could be implemented on a separate profiling machine, reported applications are all on-machine and therefore the grinding machine is non-productive during profiling. The origin of this choice can be found in the application area of form crush dressing: high accuracy diamond grinding. When reprofiling on another machine accuracy is compromised due to clamping errors, secondly it is questionable if the extra effort of changing wheels weighs up against the lost production time as most grinding systems do not have automated
tool changers (yet). The first dedicated form crush dresser that became commercially available is depicted in Figure 6-1.

![Figure 6-1: Simple free running form crushing device [courtesy of Dr. Kaiser Diamantwerkzeuge GmbH]](image)

This is a small ($d_r = 56$ mm) roll made out of a 500 µm thick CVD diamond layer. This provides for a continuous and pure diamond layer. The diamond is backed with cemented tungsten carbide to provide for the needed strength and stiffness. This form roll is connected to an axis which is, in its turn, supported by a set of precision angular contact ball bearings. The device has no drive system or sensors and can simply be installed on the machine table when needed. The shortcomings of this system are obvious: because of the lack of a drive system the form roll is accelerated every time contact is made with the grinding wheel. This leads to high wear as documented by Hessel [Hess03]. At higher speeds ($v_{sd} > 10$ m/s) investigations showed that synchronization is often not achieved at all, resulting in even higher wear. At present the application of this set-up is limited to quick and easy truing (crushing of a straight profile). For this purpose it was used and proven satisfactory to remove for example 70 µm run-out of a vitrified diamond grinding wheel in just a few minutes.

To create a system truly capable of form crushing of profiles Hessel showed that a drive system for the form roll is necessary [Hess03]. A sketch of the system used in his research is shown in Figure 6-2. From this figure the increased system complexity becomes clear: The form roll is driven by an electric motor. This motor is powered by a frequency converter that receives a set-point value $n_r$,set from a controller. The controller determines the speed set-point based on the measured rotational speeds of the grinding wheel $n_s$, the form roll $n_r$,real and of an extra measurement of the distance between the form roll and grinding spindle axes $\Delta a$. These measurements ask for three extra sensors when they are not already available in the machine tool control. The input $d_r$ is necessary for the controller to translate rotational into circumferential speeds. This value is entered into the control by hand and the effect of progressing wear on the form roll diameter $d_r$ is not taken into account.

The practical lay-out of two of these systems is shown in Figure 6-3.
The system shown in Figure 6-2 makes use of a velocity control. This implies that the calculated speed set-point for the control should exactly match the actual surface speed of the grinding wheel. As this appears to be a major limitation of the system, its properties are extensively dealt with in chapter 7.

Apart from its accuracy and flexibility a significant advantage of form crushing is that the diamond profiling process can be executed unattended. This enables fully automated grinding. However wear of the form roll is a limiting factor: when worn the roll has to be exchanged manually and the worn roll is sent back to the manufacturer for re-grinding of the roll (this is covered in more detail in chapter 8). This interrupts the production and operator intervention is needed. Furthermore a set of form rolls is needed leading to considerable capital investment. In the present situation a set of three rolls seems to be the minimum: one on the machine, one for direct replacement and one that is being processed by the re-grinding company. Depending on the activity of the end-user and the processing time for regrinding this number can be higher.
The accuracy of the form crushing method is limited primarily by:

-1- Form roll wear.
-2- Motion accuracy of the profiling device.
-3- The crushing process.

Form roll wear is dealt with by periodically changing of the roll. The motion accuracy is in the current solutions determined by the motion accuracy of the grinding machine. Errors when mounting a new or reground form roll also limit the accuracy. In principle conventional form dressing systems can also be run at the crushing speed ratio of \( q_d = 1 \) to enable form crushing, however more slip will occur along the grinding wheel profile which will result in more wear of the form roll and therefore reduced accuracy.

The crushing process itself also limits the accuracy as every dressing process damages the grinding wheel to some extend. This will be dealt with in later chapters.

The flexibility of form crushing is presently limited by:

-1- The tip radius of the form roll \( (R_{\text{top}} = 200 \mu m) \).
-2- The top angle of the form roll \( (\theta_{\text{top}} \geq 40^\circ) \).
-3- The smallest grinding wheel grain size that can be used (currently D12-22).

The tip radius of the form roll defines the smallest internal radius on a profile that can (theoretically) be made. An infinitely small radius would result in maximum profile flexibility; however that is practically not feasible as smaller radii lead to increasing profiling time and increased radial wear due to the small contact surface. Published results by Hessel [Hess03] where all achieved with a 0.2 mm top radius.

The top angle of the form roll defines the steepest angle that can be created in the profile. Form roll top angles as small as \( \theta_{\text{top}} = 40^\circ \) can be made, leading to the largest achievable profile angle of 70°. Smaller top angles than 40° are difficult as the form roll is weakened too much.

The grain size of the grinding wheel determines the “resolution” of the process as in crushing complete grains are removed from the grinding wheel. So far experiments with grain sizes below D12-22 failed to result in a usable grinding wheel.

The form roll top angle is a property of the form roll that cannot be influenced. The radius of the form roll might be made smaller and adapted to the specific profiling task at hand. Principally there seems to be no reason why smaller grain size grinding wheels should not be crushable, therefore it is expected that this behavior is influenced by the properties of the profiling set-up and used process parameters.
Various users [Hess04], [Denn04] of the velocity controlled systems have indicated issues that need attention:

-1- Profiling times are long.
-2- Integration of the equipment on an existing machine is difficult and expensive.
-3- The system is susceptible to vibrations, especially at higher speeds.
-4- The system is expensive, both the initial cost and the operational cost.
-5- Limited performance of form roll control system at speeds $v_{ac} \geq 10 \text{ m/s}$.

To points 1 and 4 should be added that there is no profiling method that can reach comparable accuracy and detail at present. However customers might have an indication for the added value of the process and have insight in the price their customers are willing to pay for the increased product quality, motivating this statement. Furthermore during dressing the grinding machine cannot grind and therefore this time has to be considered as non-productive and has to be minimized. The initial cost of the available system is currently (based on price of 2007) around € 21,500 (excl. installation), a form dressing system would be available for about half this price. Furthermore the purchase and regrinding cost of the form roll can add up: a roll costs around €2000 and regrinding €400.

Point 2, the integration on the machine, is especially troublesome as far as the communication between the existing machine tool and the profiling device is concerned. Not all control systems have an open architecture and even when integration is possible it takes considerable effort. The main integration issue is concerned with the measurement system for the distance between the form roll and grinding wheel centres, $\Delta a$.

Point 3, the susceptibility to vibrations is process related: crushing processes are known for being sensitive to vibrations. These vibrations compromise the grinding wheel integrity and thereby the achievable accuracy. Furthermore by limiting the achievable crushing speed the economy of the process is also compromised. A profiling device that is capable of crush dressing should therefore be able to cope with this process. When the lay-out of the two crushing set-ups in Figure 6-3 is given a closer look, it is observed that the crushing spindle is clamped close to the backside of the spindle. This will have a negative effect on the stiffness of the setup. Apart from the static stiffness this system will also show flexible modes due to deformation of the suspended structure and the clamp. The deformations that lead to displacements of the form roll will mainly be in the structural steel components, having very low material damping. This makes the system susceptible to vibrations. The motivation to clamp the spindle at the indicated position is probably practical: in this way interference of the clamp with other parts of the machine tool is avoided. Practical considerations compromising performance are common in the machine tool industry as designs have to satisfy many more demands than pure (dynamic) performance [Derk04].
Point 5, the limited performance of the form roll control system at high speeds is due to the low bandwidth of the control system [Hess03]. This leads to increased deviations of the intended speeds at increased speeds, leading unavoidably to increased wear.

6.1.2 Proposed method of use for flexible and high-precision form crushing

To move the present state-of-the-art a step further it is necessary to regrind the form rolls on the grinding machine. This can reduce the cost (which is detailed in chapter 8) and increase the accuracy by avoiding clamping errors. Furthermore it will become possible to regrind the form roll more frequently and therefore to keep tighter tolerances than achieved at present. Practically this will lead to more frequent regrinding of the form rolls instead of wearing the roll completely down before sending it back for reworking. The end-user will be less dependent on the delivery of the reground form rolls and fewer rolls will be needed, reducing capital investment. This way of working will also increase the flexibility of the end-user in deciding on the wear limit and needed form roll tip radius. Depending on the cost of on-machine regrinding this might also bring an economical benefit; this is researched in chapter 8.

If the regrinding of the form rolls can be automated this opens the door to completely automated and unattended high accuracy diamond profile grinding. Only to be interrupted when the diamond layer on the form roll is completely worn out (this layer can be up to 5 mm thick).

6.1.3 User requirement list

Based on the considerations in the previous section a list of requirements from the perspective of the end-user can be created, also called a customer requirements list [Pahl07], this list is shown in Table 6-1.
6.2 Design requirements on the form crushing device

The above mentioned list contains customer’s requirements that are translated into more concrete design requirements in the following section. First the requirements that are relevant for industrial application are considered (6.2.1). In 6.2.2 requirements and considerations concerning the research application of the set-up are discussed. As a result in 6.2.3 a design requirements list is formulated.

6.2.1 Design requirements for industrial application

Profile diamond grinding wheels with high accuracy

The accuracy referred to by the customers is the accuracy of the end product. This accuracy is determined by properties of the grinding process; that is the ability to transfer the profile from the grinding wheel to the workpiece, and of the dressing process; which is to create the profile into the grinding wheel. The latter is dependent on the accuracy of the motion of the profiling device as well as the performance of the crushing process itself (the extent to which the path traveled by the form roll is duplicated into the grinding wheel). Only the accuracy of the motion of the profiling tool is considered in the design phase. The other influences are the subject of the process research presented in chapters 8 through 10.

The repeatability of available profile grinding machines is in the order of 1-3 µm and the resolution of the measuring systems used about 0.1 -1 µm. The profiling device should achieve a comparable
repeatability. The absolute accuracy of these machines is strongly influenced by thermal deformations. During operation these deformations can be strongly reduced by adequate temperature control of both the machine and the surroundings. In the design phase thermosymmetric design and the avoidance of heat sources can reduce thermal deformations.

**Profile diamond grinding wheels with high accuracy - kinematics**

The kinematics of the form crushing process demand a drive system for the form roll that is able to maintain the surface speed of the form roll at the grinding wheel speed: \( v_{sd} = v_{rd} = 15 - 40 \, \text{m/s} \).

Another point of attention is the running accuracy of the form roll (run-out). As the profiling depth can become as small as \( a_{ud} = 1 \, \mu\text{m} \) in form crushing, the run-out of the form roll should be considerably better. As a design goal a run-out of 0.2 \( \mu\text{m} \) is set.

The radial and axial feed motions are principally created by the grinding machine. In [Hess03] typical feed speeds of \( v_f = 100 \, \text{mm/min} \) are used, which is well in the range of the machine. When the proposed design compromises these speeds, further evaluation is needed. For the moment it is assumed that the design will not affect feed speed.

**Profile diamond grinding wheels with high accuracy - structural properties**

The demand on the stiffness and the damping of the structure should be made more concrete. First of all the static stiffness should be sufficient to be able to generate the demanded profiles within their accuracies. As will be shown later the crushing forces vary strongly, but based on [Hess03] it can be assumed that crushing normal forces will be below \( F_{nd} = 10 \, \text{N} \) and axial forces below \( F_{ad} = 4 \, \text{N} \). To be able to reach a contour accuracy of 1 \( \mu\text{m} \) a static (total) stiffness of \( C_{tot} = 10 \, \text{N/\mu m} \) would therefore be needed. As indicated in chapter 5 the grinding machine has on the main spindle a stiffness of \( C_{mach} = 20 \, \text{N/\mu m} \). The stiffness of the profiling device \( C_{prof} \) and the machine stiffness \( C_{mach} \) act in series and therefore:

\[
\frac{1}{C_{tot}} = \frac{1}{C_{mach}} + \frac{1}{C_{prof}}
\]

(6-1)

Leading to a design stiffness of the device of \( C_{prof} = 20 \, \text{N/\mu m} \). As far as vibrations are concerned these have to be kept at an acceptable level. This can be quantified based on the depth of cut in crushing which is in the range of \( a_{ud} = 1-6 \, \mu\text{m} \) [Hess03]. It is expected that the most important effect of vibrations is that the effective crushing depth is increased momentarily, leading to increased forces and damage to the grinding wheel structure. Therefore the vibration amplitude should be reduced to a fraction of \( a_{ud} \). As a design goal a vibration level of 0.2 \( \mu\text{m} \) is set. This is based on the assumption that the influence of the crushing depth is present but not very pronounced, this is supported by the work of Hessel [Hess03] and the work presented in chapter 9. A way to suppress vibrations is by adding damping to the system. Quantifying in the design phase
the vibrations that will occur is difficult, especially as the input (magnitude and frequency) to the system is not known.

**Regrinding of form rolls on the machine**

Regrinding of the form rolls is a process in itself. This process has to be developed, which will be done in chapter 8. However, the regrinding process imposes some demands on the design of the profiling device. To give insight in these demands the kinematics of the regrinding process are shown in Figure 6-4 below. The actual radius grinding is shown in Figure 6-4c. The grinding wheel makes an axial oscillating motion along axis Z and the form roll can be swiveled around the centre of the form roll tip radius via axis A'. The oscillating motion averages out the wear of the grinding wheel over its contact width. The swiveling motion creates the radius.

![Figure 6-4: Kinematics of form roll radius grinding](image)

The grinding wheel is fed into the form roll incrementally via axis Y. Before grinding can be started, the centre of the (worn) form roll top radius should be located in the rotation centre of axis C', which is made possible by the additional adjustment motions Y' and Z'. All these motions have to be provided for in some way in the total profiling system. The motions Y and Z are present in the grinding machine. The other three motions have to be provided for in the profiling device. These motions are:

-1- Swiveling motion of the form roll, for regrinding the top radius this results in a demand on the swivel axis of +/- 70 degrees (based on $\theta_{tip} = 40^\circ$)

-2- Axial adjustment of the form roll: this adjustment should be able to position the form roll in the right position and have sufficient adjustment range to be able to use the full height of the diamond layer (max. 5 mm).
Radial adjustment of the form roll: this adjustment is only needed in the beginning when a new form roll is mounted. As it will stay on the device till it is worn out no further adjustment is needed till that moment. The adjustment range should be enough to compensate the manufacturing tolerances of the profiling device as well as the form roll. A range of 0.1 mm is therefore sufficient.

Documented values for the needed motions are rare but according to [NW85], which is concerned with SiC grinding of diamond wheels, 50 oscillations per minute (0.8 Hz) is common. It is known that the swiveling motion is slower than the axial oscillation. Therefore a maximum swivel speed of 1 rotation per second is expected to be sufficient. Form roll circumferential speeds are below the grinding wheel speeds, therefore lower than during crushing, thereby not putting an extra demand on the form roll speed.

Reduce profiling operational cost and time

Profiling operational cost is partly determined by the profiling time. Influencing the profiling time by the design of the device is possible by enabling the use of higher crushing speeds and depths of cut. This relates back to the demands on the stiffness and kinematics as discussed above. The re-grinding of the form rolls on the machine is another way to reduce operational cost, as less form rolls are needed (reducing capital investment) and regrinding cost can be saved. In chapter 8 these costs are considered in more detail.

Wide variety of grinding wheel sizes and types

End-users of the profiling device would like to be able to profile all types of grinding wheels. The profiling device aims primarily at flexible high-accuracy crush-profiling of diamond grinding wheels. However, from a tooling point of view form dressing of conventional and super-abrasive wheels is possible on a comparable set-up. In this way a very broad range of grinding wheel types is covered. Profiling of resin and metal bonded grinding wheels is however not taken as a requirement as the necessary profiling processes are very distinct. With specific adaptations to these bond systems they can in certain situations be profiled as will be demonstrated in chapter 9.

Customers also would like to be able to choose the grinding wheel dimensions depending on the grinding task and not being restricted by the profiling task. As the device is developed as an add-on to a surface grinder the grinding wheel dimensions that are used on these machines should be considered. On the other hand this wish should be balanced with the demand for a small device as the device might take up more working space on the machine when it is designed for larger wheels.

The grinding machine used in this research can take wheels with a maximum of \( d_s = 400 \) mm and \( b_s = 80 \) mm. Most used in industry are grinding wheels of \( d_s \leq 350 \) and a width \( b_s \leq 40 \) mm. Therefore this is taken as the design requirement. The smallest grinding wheels to be used have \( d_s = 60 \) mm, with the aid of the special adapter which was shown in chapter 5. This range covers the needs of most end-users.
Broad range of achievable profiles

The range of achievable profiles is limited by the top angle and top radius of the form roll, the kinematics and dynamics of the system, the grain size of the grinding wheel and the process performance. The latter two will be dealt with in later chapters (see chapters 9 and 10).

To remove the limits introduced by the top angle, see Figure 6-5, it is necessary to swivel the form roll relative to the grinding wheel to tilt the top angle away. To avoid full contact between the flank of the grinding wheel and the flank of the form roll an extra tilting angle of 5 degrees, to create a relief angle, should be provided for. As the top angle is 40 degrees, half the top angle plus the relief angle amounts to a swivel action of +/- 25 degrees. As this is clearly below the swivel range demanded for regrinding, mentioned earlier, no extra design demand is derived. The swivel speed is kept at the same value as specified earlier: 1 rotation per second.

![Figure 6-5: Swiveling of form roll to remove limitation imposed by form roll top angle](image)

The limit of the top radius of the form roll, also illustrated in Figure 6-5 cannot be removed completely, as this would lead to the demand for an infinitely small radius, however by enabling re-grinding of the form roll on the machine the top-radius can be adapted to the profiling task at hand. According to manufacturers of form rolls top radii as small as $R_{top} = 50 \mu m$ are achievable. As an upper limit a value of $R_{top} = 0.5 mm$ is set.

Based on interviews with end-users of profiled diamond grinding wheels the depth of the profiles that have to be created is relatively small, often below 1 mm. However for CBN and conventional grinding wheels deeper profiles are more common. To maintain the general applicability and anticipate the use of deeper profiles in diamond wheels in the future a profile depth of 10 mm is taken as a design requirement.
Include sensors to monitor the profiling process

Monitoring of the profiling process is attractive as this enables to remove exactly the amount of the grinding wheel layer that is needed for regenerating the profile, which will lead to a reduced profiling time and reduced use of the (expensive, super-abrasive) wheel [Karp00]. Profiling operations performed without monitoring always remove some extra material “just to be sure”. In science as well as industry the use of acoustic emission sensors is widely accepted and documented [Karp01], [Falk95], [Inas85], [Karp06] and industrial solutions are readily available. These sensors can detect primarily contact between the grinding wheel and the form roll, although the signals do contain much more information. The sensor should be able to detect the spectrum generated in crushing.

Minimum space requirement on machine

The profiling device will be an add-on to existing machines. These machines have at least three axes. To be able to use these axes, the device has to be placed somewhere in the working area of the grinding machine. This will unavoidably limit the effective working area of the grinding machine. Limiting this space requirement is therefore required. Maximum dimensions for the design are set at: length x width x height = 500 x 350 x 300 mm, as this will fit on a wide variety of surface grinders.

It has to be taken into account that part of the set-up can be located just outside the working area of the machine, as in principle only the form roll has to be in the working area.

Ease of integration on machine

Mechanical integration should be kept simple by:

- Providing a common interface to attach the device to the grinding machine.
- Keeping the external dimensions simple (e.g. no odd shapes extending from the device into the working area).
- Minimizing the problems associated with cable and hose routing.

The most straightforward way of easing integration with the NC is by avoiding the need of communication between the profiling device and the grinding machine. An example how this can be achieved is introduced in chapter 7.

Retrofit to standard 3-axis surface grinding machine

To achieve the accuracies mentioned in this project the use of numerically controlled (NC) grinding machines is necessary. However a large amount of these machines (used to) use proprietary NC controls which makes integration difficult. It is therefore wished that the device can also be used without receiving commands from the grinding machine. Modern machines do however have an open NC structure enabling the integration of extra axes and PLC controls. These functions can
therefore be used, but should not be vital in such that it makes the use of the device on a machine
with a proprietary control system impossible.

Secondly integrating the device on a grinding machine implicates that the design should be able to
function in the harsh environment of a grinding machine: water, oil and sludge with an abrasive
content are all present and should not compromise the functioning of the device.

6.2.2 Design requirements for academic application

The profiling device that is developed will in first instance be installed in a laboratory to perform
research into the form crush profiling process. This application creates some extra demands on the
device. Furthermore it influences some design decisions in the sense that performance and control
are prioritized over cost issues for this first prototype. However this should be done with reason:
the developed device should be transferable to industry without major modifications or influence on
the process.

Force measurement

For research purposes monitoring of the dressing (particularly: crushing) forces is demanded. Dressing
normal forces are typically \( F_{\text{nd}} < 10 \) N and axial forces \( F_{\text{ad}} < 4 \) N. Primarily measurement of
quasi-static forces is used in research, but there is a wish to be able to measure with such
bandwidth that variations along the circumference of the form roll can be measured to study the
effects of the rotational speeds of the two bodies on the profiling process. In this case the
bandwidth should be at least 10 times the rotational speed of the form roll.

6.2.3 Design requirements list

The preceding discussion results in a design requirements list which is shown in Table 6-2.
### Design requirements list

- Repeatability of contour as good as grinding machine or 1 \( \mu \)m.
- \( v_{sd} = 15-40 \text{ m/s} \).
- Design should not compromise feed speeds.
- Total static stiffness \( C_{prof} > 20 \text{ N/\( \mu \)m} \).
- Vibration level below 0.2 \( \mu \)m \( \rightarrow \) add damping in main load path.
- Swiveling axis form roll +/- 70 degrees.
- Radial adjustment form roll, range 5 mm.
- Axial adjustment form roll, range 0.1 mm.
- \( R_{tip} = 0.05 - 0.5 \text{ mm} \).
- Profile depth up to 10 mm.
- Grinding wheel diameter \( d_s = 60-350 \text{ mm} \).
- Grinding wheel width \( b_s = 5-40 \text{ mm} \).
- Integrate acoustic emission system for contact detection.
- Crushing forces:
  - \( F_{sd} < 10 \text{ N} \).
  - \( F_{sd} < 4 \text{ N} \).
- Provide means to measure profiling forces:
  - Demanded: normal forces, quasi-static (average forces).
  - Wished: axial forces.
  - Wished: dynamic measurement (bandwidth \( \geq 10 \times n_{sd} \)).
- Total dimensions length x width x height \( \leq 500 \times 350 \times 250 \text{ mm} \), but minimize wherever possible, concentrate auxiliary functions outside working area.
- Use on surface grinders with proprietary control principally possible (small changes or additions allowed).
- Use in grinding environment: water, oil and sludge present. Sludge will contain abrasive particles.

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**Table 6-2: Design requirements list for profiling device**

### 6.3 Design alternatives for the different functions of the profiling device

In this section the functions needed for the profiling device are identified and for every function design alternatives are suggested and evaluated. In the subsections below every function is treated separately.
Based on the design requirements list in the previous section, the following (main) functions are identified.

Main functions:
- Moving the form roll along the grinding wheel profile.
- Supporting the form roll and facilitating rotation.
- Controlled swiveling of the form roll.
- Adjusting the form roll position axially.
- Adjusting the form roll position radially.
- Driving the form roll and controlling its speed.

6.3.1 Moving the form roll along the grinding wheel profile
As the grinding machine is already equipped with three axes that enable positioning the grinding wheel relative to the worktable these axes can be used, provided that this option creates the required accuracy. It would not be technically or economically justifiable to add extra axes for these motions. The contour accuracy is thereby principally determined by the grinding machine and not the profiling device. This function is therefore pulled outside the system boundary. However care should be taken that the other functions do not interfere with the relative motions between the grinding wheel and the form roll.

6.3.2 Supporting the form roll and facilitate rotation
The form roll should be able to rotate along its primary rotation axis to create the profiling speed \( v_{rd} \). This function is fulfilled by a rotary bearing. Bearings are available in many different types all having their advantages and disadvantages. As for other functions bearings are used as well, in Table 6-3, 7 different bearing types are compared. These bearing types are evaluated on the following topics: achievable motion accuracy, friction/power consumption, stiffness, space requirement, complexity, load capacity, dynamic behavior (damping), and achievable speeds.

For the primary rotation of the form roll the stiffness should be relatively high and the running accuracy very high as it was specified at 0.2 µm run-out. Also this is the bearing with the highest speed, it is therefore advantageous to keep the rotating mass low and locate the bearing as close to the form roll as possible. As this bearing will be close to the form roll the damping characteristics are important. It follows from Table 6-3 that the hydrostatic bearing design is the most advantageous in these fields. The drawbacks: space requirement and especially the complexity and associated extra cost should be considered in the detail design.

The bearing configuration depends strongly on the space that is available to materialize the bearings.
### Bearing Types

<table>
<thead>
<tr>
<th>Bearing Type</th>
<th>High Accuracy</th>
<th>Low Friction</th>
<th>Low Stiffness</th>
<th>Small Volume</th>
<th>Low Complexity</th>
<th>Load Capacity</th>
<th>High Damping</th>
<th>High Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sliding</td>
<td>-</td>
<td>-</td>
<td>+/-</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rolling element</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Aerostatic</td>
<td>++</td>
<td>+++</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td>Hydrostatic</td>
<td>++</td>
<td>++</td>
<td>1</td>
<td>++</td>
<td>-</td>
<td>+</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>Aerodynamic</td>
<td>-</td>
<td>+++</td>
<td>1</td>
<td>+</td>
<td>+</td>
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<td>+++</td>
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<tr>
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<td>++</td>
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<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Magnetic</td>
<td>++</td>
<td>+++</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+++</td>
</tr>
</tbody>
</table>

1) Friction is dominated by the viscous fluid friction in the bearing gap, depending linearly on the speed of the bearing consider friction for high speed application.

2) Most applications do not use a preload, leading to play and difficult assessment of stiffness. Preloaded variants have better stiffness but are only applicable for very low speed.

3) The dynamic bearings do not function at low speeds, without any additions low speed behaviour is sliding.

4) As magnetic bearings are active, damping can be controlled within the bandwidth of the controller; at higher excitation amplitudes damping is very low.

### Table 6-3: Qualitative comparison of bearing types

In Figure 6-6 two options are studied. From a stiffness point of view the double sided support shown in Figure 6-6a is preferred. However exchanging the form roll will take more effort than in the single sided solution shown in Figure 6-6b.

Figure 6-6: Form roll bearings a) double sided support and b) single sided support

An even stronger argument to opt for the single sided solution is indicated in Figure 6-6a where the space limitation is shown when the form roll is swiveled +/- 70 degrees, there is little space to create the bearing on this side. The grinding spindle itself is also a single sided solution, by
extending the form roll spindle to the opposite side minimum interference is achieved. The single sided solution is therefore chosen for the design.

6.3.3 Controlled swiveling of the form roll

In the design of the swiveling axis the location of the centre point of the swivel axis is of utmost importance. Based on the demands of the regrinding process it was already motivated that the contact point of the form roll should be located on the swivel axis. During profiling this is also advantageous: the position of the contact point between grinding wheel and form roll will not change depending on the position of the swivel axis, this is illustrated in Figure 6-7. Figure 6-7a shows the effect of swiveling on the contact point when the contact point would not be located on the swivel axis. When swiveling the machine tool control should continuously compensate the Y and Z positions for the deviations $\delta_y$ and $\delta_z$. However that would conflict with the demand to use the device on a machine with a proprietary control. When the position of the swivel axis is chosen such that the form roll swivels around the centre of the form roll top radius, there is no need for compensation, this is illustrated in Figure 6-7b. In this arrangement swiveling does not affect the position of the contact point between form roll and grinding wheel. There is no need for communication with the machine tool control and complex motions are avoided.

![Figure 6-7: Influence of location of swivel centre: a) does not coincide and b) coincides with centre of form roll top radius](image)

Another advantage of this solution is that the positional accuracy of the swivel axis does not affect the profile accuracy. This relaxes the demands on the drive system for the swivel axis and increases overall accuracy.

The speed of the swivel axis is low. Stiffness requirements are relatively high as these bearings will be in the force transmission line. The mass between the form roll and the swivel bearing will be relatively large, making it more difficult for these parts to be excited by the process. The demand
on the damping properties is therefore less than for the form roll bearing. The run-out of the swivel axis should be related to the accuracy (repeatability) of the machine tool. This is around 2 µm. Run-out values for high precision angular contact ball bearings are specified at 2.5 µm [NNSkf]. Run-out specified for rolling element bearings consists of both synchronous run-out and asynchronous run-out. Synchronous run-out is repeatable and therefore not a problem for the swivel axis, as during grinding of the form roll radius these errors are automatically compensated. Because of these aspects it is considered adequate to use high precision ball bearings for the swivel axis. This has the significant advantage of low complexity and ease of integration leading to design freedom. Furthermore rolling element bearings are bought-in parts that reduce engineering effort.

The spatial lay-out of the swivel axis and its bearings is of major importance for the total design. Two configurations are shown in Figure 6-8. With the double sided variant a high stiffness is achievable. The single sided variant has the advantage of a strongly reduced space requirement. The space that can be saved in this way is the most relevant space as this is the space that extends into the working area of the grinding machine.

As the set-up should enable profiling of large grinding wheels \(d_s = 350\) mm) the distance indicated by \(L\) in Figure 6-8 has to be relatively large. It proved therefore not possible to achieve the required stiffness for the device with a single sided support. The main restriction here is the bending stiffness off the swivel axis. Increasing the diameter of this axis to reduce bending, results in the use of larger swivel bearings which in its turn demands for an increase in the distance \(L\), compromising total stiffness. Stiffness is prioritized over space as the design is primarily meant for high-accuracy applications. This motivates the choice for the double sided swivel support.
6.3.4 Adjusting the form roll position axially

The axial position of the form roll has to be adjusted when it is mounted on the profiling device. This to make sure that the PP axis of the form roll, shown in figure 5.5 intersects with the swivel axis. This alignment will be done in three steps:

1) The design of the device locates the contact point roughly (within 0.5 mm) in the right position (see section 6.3.3)
2) A fine adjustment locates the form roll axially within 5 μm.
3) During the first regrinding of the form roll the last deviation is removed automatically.

The fine adjustment is meant to compensate for manufacturing tolerances in both the profiling device and the form roll.

Demands on this adjustment are therefore:

- Minimum compromise on stiffness.
- Minimum space requirement.
- Resolution 0.01 mm or better.
- Frequency of use 1x per 6 months.

A simple yet effective solution is found by adding a washer between the form roll axial reference face and the locating element of the profiling device. This washer will have a nominal thickness of 1 mm that can be ground to the specified thickness, achieving the required resolution without difficulties.

After mounting a fresh form roll with a nominal size washer, the deviation can be measured, a new washer created and the roll remounted with the corrected washer. The stiffness is affected by the contact stiffness of the added interface. As long as these surfaces are prepared carefully (low roughness) and the out of plane stiffness of the washer is kept low (thin washer) this influence is small.

6.3.5 Adjusting the form roll position radially

After mounting, the form roll has to be positioned radially in the right position, which means that the centre of the tip radius should coincide with the centre of the swivel axis. The three step approach of the previous section is also valid here. Different are the adjustment range and the adjustment interval. When the form roll is worn the contact point is effectively radially displaced and needs to be re-adjusted before regrinding the form roll. The adjustment interval can therefore be as often as once a day. Quick and reliable operation is needed. The resolution of the system should be < 5 μm. In practice the form roll will be moved slightly above the ideal position and than during regrinding the final accuracy is reached. A resolution of 5 μm or better is needed to minimize the amount of diamond layer that has to be removed, reducing grinding time, form roll wear and grinding wheel wear.
An adjustment axis is composed of a guide system, an actuation system and a fixation system. The bearing principles shown in Table 6-3, can also be used for a linear guide. The adjustments that will be made per justification are very small: 10-100 µm. Adjustment speeds can therefore be accordingly small. The stiffness of the guide should be high as it is in the force transmission line. The accuracy of the guide should be within 5 µm as it would otherwise compromise the constraint on the axial position of the roll set in section 6.3.4. The demands set can be fulfilled with a sliding linear bearing, if designed and manufactured well. The other bearing principles will be unnecessarily complex. For small translations or rotations the use of elastic hinges is another proven concept [Kost00]. The basis principle of an elastic hinge is illustrated in Figure 6-9a.

![Figure 6-9: Elastic mechanisms: a) leaf spring b) leaf spring attached to body c) flexure hinge d) leaf spring translation guide](image)

Elastic hinges and mechanisms have no play, can be manufactured easily, are reliable, need no maintenance and have neither friction nor wear. As these mechanism have no sliding or rolling elements pollution of functional surfaces is less problematic, making it a potentially very robust solution.

Actuation is needed to actually move the part along the guide. The energy needed for actuation can be manual or from an auxiliary power source. The small motions and therefore energy needed enables the use of a manual actuation system. The relatively coarse action of human motion should be transferred to a controlled displacement with high resolution (5 µm). For this purpose wedges, screws, levers and eccenters are commonly used.

Fixation is applied after adjusting; the system is “frozen” in its position. Fixation might in some situation be provided by friction in the system. However, separating the fixation function enables the use of a convenient adjustment system and operating force, while being able to transfer a considerable amount of force after engaging the fixation system. Fixation systems should not need
continuous power supply as they are normally engaged. The main challenge in developing fixation systems is not to affect the position of the parts when engaging the fixation. The basic principle to achieve this is by making sure that the fixation force has no components in the direction of the guide, which could lead to displacements of the parts.

Three design alternatives for this adjustment axis are illustrated below.

**Eccentric bushing**

The use of an eccentric bushing is common practice, e.g. to radially adjust ball bearings on simple guide systems. In the profiling device the form roll spindle unit could be mounted in an eccentric bushing that will be mounted in the swivel block. In this way the guiding and actuation can be combined. In Figure 6-10 this is schematically represented. The axis of the inner and outer cylindrical surfaces of the bushing are displaced by amount e. The range of adjustment is 2·e, based on a demanded travel of 5 mm e should be 2.5 mm.

![Eccentric bushing](image)

*Figure 6-10: Use of an eccentric bushing for radial adjustment*

The form roll needs to extend at least 25 mm above the swivel block, based on the demand to be able to create 10 mm deep profiles, in 40 mm wide grinding wheels while the form roll swivels to 25º. The form roll has a radius of 60 mm, therefore the form roll spindle assembly including eccentric should have a radius of less than 48 mm and maintain the integrity of the swivel block. The eccentric bushing has to be made accurately to ensure a tight, play-free fit. To manufacture such an accurate part a minimum wall thickness of 5 mm is necessary. Fixation will be needed, radial locking screws in the swivel block could be used, local deformations of the bushing would have to be considered.

Advantages are:

- Simple design.
- Few moving parts.
- Fairly well sealed guides.
Disadvantages are:

- Difficult to make play-free.
- Parasitic motion in x-direction beside the functional motion (in y direction).
- Poor resolution when used without a special actuation system reducing the motion of the bushing the system due to stick-slip effects.
- Resolution varies depending on the angular position of the eccentric.

Combined with the space requirements for the hydrostatic bearings of the form roll this solution proved geometrically not feasible. Secondly the parasitic motion of 5 mm in X-direction is too large and would need to be compensated, leading to extra operating complexity.

**Elastic hinge adjustment**

The most common way to achieve a straight guide with elastic hinges is to use two leaf springs as is illustrated in Figure 6-9d. The double leaf spring is preferred over a single leaf spring to fix the rotation $\alpha$. For the radial adjustment of the form roll this rotation coincides with the rotational axis of the form roll. Therefore the use of a single leaf spring or flexure hinge can be sufficient. This will also lead to a parasitic translation in X-direction however, as this displacement is related to $\sin \alpha$ it can be neglected for this application as $\alpha$ is small.

A simple variant of a leaf spring solution is sketched in Figure 6-11 below. In cylinder A the form roll bearing assembly should be placed. Again a 50 mm diameter is reserved for the form roll assembly. Part C of this monolithic structure can be moved up and down by 2.5 mm. The main deformation will take place in the flexure hinge.

![Elastic hinge guide for radial adjustment](image)

**Figure 6-11: Elastic hinge guide for radial adjustment**

- From this figure the design challenges for this solution can be seen:
- The elastic element has to be designed such that a 5 mm travel can be achieved, while at the same time the thickness of the material at D and E is sufficient.
- An actuation principle should be provided for, preferably at position B. B is in line with the crushing normal force.
A fixation principle is needed as the structure elastically moves back to its initial position.

The stiffness of the construction out of the drawing plane (Figure 6-11) should be evaluated. The actuation in point B can be done with e.g. a wedge, screw or eccentric. Fixation might be omitted if the structure is designed such that the spring force of the structure is always directed against the actuator at B. In this way the contact between the actuator and part C is pre-loaded and the position defined.

During the detail design phase the space limitation at D and E showed to be problematic. Furthermore several tubes and sensor cables have to cross the slot, making the structure more complex.

**Dovetail guide**

To create more space for all detailing around the form roll bearing assembly, a concept was developed that locates the adjustment system further away from the form roll bearing assembly. The principle is sketched in Figure 6-12a, as is clear from the figure the adjustment is now supported by two guides, leaving all material in between the guides free for creating the functions needed for the form roll bearing assembly. The double guide system has however a drawback: two guides now determine one degree of freedom. This can only work if the swivel block is kept horizontal under all circumstances. A means should be provided for this.

![Figure 6-12: a) Layout of double guides and b) pre-loaded swallow tail guide](image_url)

Swallow tail sliding guides leave only one translation free and can be pre-tensioned to avoid play as is illustrated in Figure 6-12b. Actuation can be provided for by a screw. The combination of swallow tail and screw facilitates a long travel. To achieve the required resolution of the adjustment axis an inconveniently fine thread would be needed. The actuation is therefore divided into two actuators in series: a coarse actuator (a standard bolt M8) and a fine tuning mechanism with an elastic hinge lever mechanism that has a limited travel but high resolution, see Figure 6-13. The moving part is connected to the upper side of the lever mechanism. The coarse screw is threaded only into the lower part of the lever and its head is supported by the stationary part. The fine adjustment screw has no contact with the stationary part but is threaded into the upper part of the lever and rests
with its face against the lower part of the lever mechanism. In this way the lever mechanism can be elastically deformed when the fine adjustment screw is tightened. This will result in the moving part moving upward by a fraction of the axial movement of the adjustment screw and a small rotation of the lower part of the lever mechanism which can be handled by the coarse thread (due to the available play).

Even though friction in the guides is high due to the preloading an extra means for fixation is provided by a mechanism that will pull the stationary and moving part firmly together.

### 6.3.6 Driving the form roll and controlling its speed

The most important function of the form roll drive system is to accelerate the form roll to the crushing speed, $v_{ad} = 15-40 \text{ m/s}$ and maintaining this speed. Given the form roll diameter, $d_r = 120 \text{ mm}$ the rotational speed of the form roll should be $40-106 \text{ Hz} \ (n_r = 2400-6360 \text{ rpm})$. Secondly the controllability of the speed of the roll should be considered. There is no information available on the needed control accuracy, this will be part of the research (see chapter 7). A measuring system to accurately measure the form roll speed is therefore needed to study the profiling process and to control the synchronization process.

The first decision when choosing a drive system would be the energetic driving principle to be used. Possibilities include: hydraulic, compressed air and electric.

- Compressed air is easy to use as no return piping is necessary. Air driven spindles are also simple and cost effective especially for high speed application; however the controllability of the rotational speed is poor.
- Hydraulic drive systems are more complex than air drives and mostly used for high torque and low speed applications.
• Electric drives are commonly used and a wide variety of standard components is available making its use straightforward. The control of these drives can be very good, depending on the type of system used.

To choose the motor size, an estimate of the needed motor power, or better torque-speed demand, is needed. When other profiling systems are studied it is seen that relatively large asynchronous electric motors are used. The systems in Figure 6-3 for example have a power of 0.45 kW and speed range of \( n_r = 1500 - 16000 \) rpm. Use can be made of form rolls with a diameter of up to \( d_r = 150 \) mm.

The power consumption of the form roll spindle is built up of three components: 1) the profiling process power, needed for the material removal and friction, 2) idle power of the spindle to overcome the friction and other losses in the spindle itself and 3) acceleration forces to accelerate the form roll.

**Process forces**

The process forces discussed below are based on form dressing. Therefore they most likely overestimate the crushing tangential forces, but are a good representative for the forces during regrinding of the form roll. [Töns92] measured a maximum change in power of 40 W of a dressing spindle due to the CBN dressing process for a wide range of dressing parameters. [Köni94] mentions tangential dressing forces below 2 N for a form roll with \( R_{top} = 450 \) µm, [Yoko93] mentions comparable values, which would lead to a maximum dressing power of 80 Watts (at \( v_{ad} = 40 \) m/s), both for vitrified CBN wheels. Shih also measured vitrified diamond grinding wheels and found specific tangential dressing forces up to \( F_{td} = 2.5 \) N/mm [Shih00]. Taking the aforementioned values into account and considering that the present design is meant for small contact width (\( b_c < 0.5 \) mm) a tangential force of \( F_{td} = 2 \) N is used. This leads to a torque demand of

\[
T_{process} = F_{td} \cdot \frac{d_r}{2} = 0.12[Nm]
\]

for \( n_r = 2400-6360 \) rpm.

**Spindle friction**

The spindle idle power is dominated by the friction in the bearings. As hydrostatics is chosen for this purpose (see section 6.3.2) the friction torque is linearly dependent on the bearing speed as the torque is related to the deformation speed of the fluid in the bearing. Therefore the bearing power is related to the speed squared. In Appendix A the friction torque of the bearing system is calculated at:

\[
T_f = 4.46 \cdot 10^{-5} \cdot \omega_f
\]
This results in a maximum friction torque of 0.03 Nm and a power of below 20 watts.

**Acceleration**

Acceleration torque is for most profiling processes only needed to speed up the form roll before starting the process, as the speed of the form roll is kept constant during the process. For this purpose a run-up time of 2 seconds is set. For the special case of form crushing the form roll should also be accelerated along the grinding wheel profile. An estimate for these accelerations can be made by assuming the form roll is fed radially into the grinding wheel at small overlap ratio, \( U_d = 2 \), small contact width, \( b_d = 60 \mu m \), high profiling speed \( v_{ud} = 40 \text{ m/s} \) and a small grinding wheel diameter, \( d_v = 60 \text{ mm} \). This leads to \( n_v = 12700 \text{ rpm} \), \( v_i = 381 \text{ mm/min} \) and a relative momentary radius change rate of 0.21 \text{ 1/s}. At \( n_v = 12700 \text{ rpm} \) = 1602 \text{ rad/s} this results in a maximum acceleration of 339 \text{ rad/s}^2. The acceleration torque is derived via:

\[
T_a = I_r \cdot \dot{\omega}
\]

In which \( I_r \) is the mass moment of inertia of the complete rotor. For a cylinder \( I \) can be expressed as:

\[
I_{\text{cylinder}} = \frac{1}{32} \cdot \rho \cdot l \cdot \pi \cdot d^4
\]

with \( \rho \) the density of the material, \( l \) the length and \( d \) the diameter of the cylinder. As the form roll diameter will be considerably larger than the other elements of the rotor and \( I \) is dependent on \( d \) to the power 4 the rotor mass moment of inertia can be approximated by the form roll dimensions: \( l=10 \text{ mm} \) and \( d_r = 100 \text{ mm} \), \( \rho = 7.8 \cdot 10^3 \text{ kg/m}^3 \) and therefore \( I_r = 7.66 \cdot 10^{-4} \text{ kg} \cdot \text{m}^2 \). Which leads to a maximum acceleration torque of \( T_a = 0.26 \text{ N\cdotm} \). This torque is an absolute upper limit as the estimate is based on extreme values.

Combining these three contributions the required torque for the motor becomes:

\[
T_m \geq 0.38 + 4.46 \cdot 10^{-5} \cdot \dot{\omega}
\]

for \( n_r = 2400-6360 \text{ rpm} \).

The form roll can be driven either directly by attaching the motor directly to the form roll or indirectly via a drive train e.g. a belt, chain or friction drive. A direct drive system has less components and in principle less rotating mass leading to a better controllability of the system. The main drawback of a direct drive system is that the motor will be mounted in-line with the form roll axis and the total length of the assembly might not fit the design space. Therefore the axial dimension of the motor should be kept as small as possible; the radial dimension (diameter of the stator) is allowed to be larger. These considerations have to be dealt with in the detail design phase.
6.4 System composition and design

In this section the most promising design solutions are combined into a conceptual design. First the total design of the profiling device is introduced in 6.4.1. Next the detail design of the form roll spindle system is elucidated in more detail.

6.4.1 Concept design

In Figure 6-14 below, the design of the profiling device is shown. The form roll is indicated in the back view. The swivel kinematics and double swallow tail guide system discussed above are easily recognized. The swivel axis is driven by a servomotor via a 1:50 play-free reduction and a belt drive (in the isometric view the cover plate is removed to show the belt drive). The standard motor encoder of the servo for position feedback proved sufficient (an indirect measuring system), simplifying the design.

When designing this structure the static design stiffness of $C_{prof} = 20\ N/\mu m$ was used as a starting point. As damping was demanded use was made of hydrostatic bearings. Damping is related to velocity (or: rate of displacement), therefore in this design the displacements are concentrated in the elements that have most damping. Effectively this has resulted in a set of hydrostatic bearings.
for the form roll with relatively low stiffness (see 6.4.2) and a rigid supporting structure. The pressurized fluid for the hydrostatics is fed into the device via the swivel journal at the swivel drive side (in red). From there the liquid is routed through the different parts to the form roll bearings. This avoids external hoses in the workspace. In traditional hydrostatic systems return piping is then used to guide the fluids back to the high pressure pump. This is needed to protect the rest of the machine and the environment from the hydraulic fluid and keep the fluid clean. By using the grinding fluid as hydraulic medium the fluid can simply be spilled into the machine which avoids the need for return piping. Extra care should however be taken in cleaning the fluid before using it for the bearing again.

In Figure 6-15 the design is shown in its extreme positions, together with the (small) grinding spindle illustrating that swiveling over the full range (+/- 70 degrees) is possible without interference.

![Figure 6-15: Designed profiling device in extreme swivel positions combined with small wheel adapter](image)

**6.4.2 Detail design of the form roll spindle system**

In Figure 6-16 a cross section of the form roll spindle system is shown [Derk06]. The form roll is centered on the right extension of the form roll axis with a tightly tolerated cylindrical fit and axial defining surface and locked with a washer and locking nut. In this way the position of the form roll can be guaranteed down to several µm. When regrinding the form roll this last tolerance is removed. The form roll axis is held by a radial bearing bushing and an axial bearing (not indicated...
in this figure). At the left hand extension the rotor of the servo motor is mounted to the axis with a keyless frictional locking device. Behind the rotor an incremental position encoder is mounted and an acoustic emission sensor is bolted to the face of the axis, transmitting its signal wireless to the AE receiver [NNDitt].

In the sections below the hydrostatic bearing, force measuring system and form roll drive are discussed in more detail.

**Hydrostatic bearing concept**

Below a qualitative and functional description is given of the hydrostatic bearings used in the form roll spindle. More detailed calculations can be found in Appendix A.

In a hydrostatic bearing a pressurized liquid is used to separate the bearing surfaces and carry the load. In Figure 6-17a the principle is shown: the supply pressure $p_s$ is reduced in resistor $R_1$ to the bearing pocket pressure $p_r$. From the pocket the fluid flows out of the bearing via the lands, reducing the pressure to the ambient pressure $p_a$. In Figure 6-17b this is shown schematically. If now a force $F_{load}$ is applied to the bearing the gap width over the land reduces, increasing resistance $R_2$. $R_1$ does not change, this leads to an increase of the pressure $p_r$ from $p_{r,uld}$ to $p_{r,ld}$, thereby increasing the reaction force of the bearing and compensating the extra load. In other words: the series arrangement of the two resistors adds stiffness to the bearing. Without any preload force $F_{pre}$ the bearing is not able to support loads in negative Z-direction.
In Figure 6-18 another concept is shown, here two bearings are arranged opposing, thereby pre-loading one another. Furthermore the bearings have integrated restrictors [Kraa77]. Consider the supply pressure \( p_s \) present at the right hand side and the ambient pressure at the left hand side. The fluid will be forced to flow via the first land (restrictor \( R_1 \)) to the small pocket. In this pocket the fluid is collected and guided to the other side of part \( C \) into the bearing pocket \( B \). If a displacement of part \( C \) in positive \( Y \)-direction is considered the resistance \( R_1 \) is increased leading to a reduced pressure in the bearing pocket \( B \). Furthermore resistance \( R_2 \) is increased leading to a higher pressure in bearing pocket \( A \). At bearing \( B \) the opposite effect will happen. In this way the resistance of the restrictors is not constant as in Figure 6-17 but varies according to the load. In this way a higher stiffness of the bearing can be created. Another advantage of this construction is that the restrictors can be integrated into the bearing parts reducing the amount of components and manufacturing tolerances. Tuning of restrictors and variances due to manufacturing tolerances are also avoided in this way.

The resistance \( R_s \) is only there to separate the two pockets of bearing \( A \). It should be chosen as high as possible to reduce leakage from the small collection pocket to bearing pocket \( A \). On the
other hand this land uses effective area of the bearing reducing stiffness and load capacity. Careful
optimization is necessary, details can be found in Appendix A.

The double acting bearing with integrated restrictors can be extended to a journal bearing by
arranging several pockets in a circular way. 6 pockets are found to be optimal [Kraa77]. In Figure
6-19 an arrangement of a complete spindle is shown. Two radial bearings with integrated restrictors
are used (with each 6 pockets on the circumference) and combined with a conventional axial
bearing with an external restrictor to take up the axial loads. Because the supply pressure is present
at the diameter reduction of the axis a pre-loading force equal to:

\[ F_{\text{pre}} = \frac{1}{4} \pi \cdot \left( d_{\text{rad,1}}^2 - d_{\text{rad,2}}^2 \right) \cdot (p_s - p_a) \]  

(6-7)

is present enabling the bearing to carry loads in positive Z-direction (up to \( F_{\text{pre}} \)).

![Figure 6-19: Hydrostatic spindle concept: Radial spindle bearings with integrated restrictor and
single pre-loaded axial bearing with external restrictor](image)

An extra advantage of this arrangement is that the two radial bearings are supplied with fluid over a
land, while in a conventional design fluid exits a journal bearing via both lands. In this way the
volume flow of the bearing, and therefore energy consumption, are reduced.

A cross section of the form roll spindle design is shown in Figure 6-20. As in Figure 6-19 the form
roll axis is supported by two radial bearings and a pre-loaded axial (or thrust) bearing. The axial
bearing is ring shaped to facilitate the axis to extend past the bearing on the left hand side to
provide place for mounting the drive system. The thrust disk is assembled in a sliding way with two
rubber O-rings in the drive flange. Between the two O-rings, the thrust disk and the drive flange the
axial bearing pressure pressure \( p_{\text{ax}} \) is present, forcing the thrust disk tightly against the face of the
radial bearing bushing. This construction is chosen to facilitate manufacturing of the bearing
components. In this way the thrust disk only has to be tolerated tightly on its flatness, which is
easily achieved in manufacturing. The radial bearing bushing face should be square to the radial
bearing surfaces. Without the use of the thrust disk the tolerance chain would be longer and the
parts therefore more complex to manufacture.
For the axial bearing use is made of a laminar cylindrical gap restrictor, located inside the axis. The hydraulic fluid is supplied at the inlet and enters into the rotating axis via 4 bores. These bores lead to a central bore in the axis where the gap restrictor is located. Over this restrictor the pressure drops to half the supply pressure for maximum stiffness [Beek04]. The fluid is then supplied to the ring shaped axial bearing pocket.

The radial bearing bushing is a complex part as it carries all the details for the integrated restrictors and the channels that have to direct the fluid to the opposing pocket and is shown in Figure 6-21. The spiral groves direct the flow to the opposing pockets. This bushing is shrink-fitted into a bore in the swivel block.

At the motor side of the axis, just behind the thrust flange, a rubber seal is located to avoid hydraulic fluid entering the motor compartment. The motor compartment is kept at a pressure
above ambient level with a flow of pressurized air, for extra security. Secondly the air escaping between the rubber seal and the axis reduces the contact force between the two and thereby the friction of the seal. At the form roll side a contact-less air seal is located keeping the hydraulic fluid inside the bearing.

As a hydraulic fluid, hydraulic oils are most commonly used. A disadvantage of oil is that the friction is rather high and that it should not mix with the grinding fluid used in grinding machines. In this design the (water-based) grinding fluid is used as hydraulic medium. Therefore spilling of the fluid into the machine is allowed, simplifying the design. In principle return hoses become superfluous at all. The high pressure pump can take the grinding fluid from the machine sump, filter it and send it to the profiling device that spills it into the machine. An extra advantage is that on precision grinding machines the grinding fluid is thermally conditioned, thereby avoiding the need for a separate oil-chiller as used in conventional closed hydrostatic systems. As the grinding machine used for this project uses water based grinding fluids consisting out of 95% water and 5% synthetic water soluble oil, the viscosity of the fluid is comparable to water (20 times lower than thin oil). This lower viscosity leads to lower friction in the bearing, but also to an increased flowrate (and therefore energy consumption) and losses in the pump.

The full bearing calculations can be found in appendix A. Below some results are summarized:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial stiffness</td>
<td>53 N/µm</td>
</tr>
<tr>
<td>Largest resp. smallest diameter axial bearing</td>
<td>32 resp. 17 mm</td>
</tr>
<tr>
<td>Flow axial bearing</td>
<td>5.3 l/min</td>
</tr>
<tr>
<td>Radial stiffness at form roll position</td>
<td>65 N/µm</td>
</tr>
<tr>
<td>Diameter radial bearing 1 resp. 2</td>
<td>30 resp. 34 mm</td>
</tr>
<tr>
<td>Length radial bearing 1 resp. 2</td>
<td>30 resp 20 mm</td>
</tr>
<tr>
<td>Flow radial bearing 1 resp. 2</td>
<td>2.5 resp. 2.9 l/min</td>
</tr>
<tr>
<td>Total flow</td>
<td>10.7 l/min</td>
</tr>
<tr>
<td>Total friction torque at 6000 rpm</td>
<td>0.028 N·m</td>
</tr>
</tbody>
</table>

Table 6-4: Form roll hydrostatic bearing properties

**Force measuring system**

As the main research on the device is crush dressing, normal forces are considered the most important. In many researches tangential profiling forces only are measured. These are then derived from either grinding or profiling spindle power [Shih00], [Geis80]. This cannot be done for the normal forces. Dressing normal forces are most commonly measured in profiling research by
placing the complete profiling device [Inas89], [Gels80] or even the machine table [Hess03] on a piezo capacitive force measuring platform. The forces can also be measured on the grinding wheel side [Cina94].

Piezo capacitive sensors have the advantage of having a wide range and high resolution combined with a relatively high bandwidth. Their main drawback is drift: static measurements are only reliable for a relatively short period of time and careful zeroing before starting a measurement is needed. Piezo capacitive sensors are therefore used primarily in laboratories. In industry piezo resistive sensors and strain gauges find more application due to the absence of drift. As the force measurement system is meant only for research piezo capacitive sensors are chosen.

To get the best results (bandwidth) the forces should be measured as close to the contact point as practically possible. Therefore placing the whole device on a force measuring platform is not optimal. As hydrostatics are used for the bearings of the form roll axis there is a direct relation between the pressure in the bearing pockets and the forces on the form roll. Therefore two piezo capacitive pressure sensors are installed that measure the pressure in the bearing pockets. One sensor is connected to the pocket of the axial bearing to measure the axial force and the other to the lower pocket of the front radial bearing to measure the radial profiling force. An evaluation of this system is given in 6.5.5.

Servo motor drive

A solution for the space restrictions is found in a frameless brushless servo motor package existing of a stator with the windings and a rotor with 12 magnets that can be mounted directly on the form roll axis. In this way an extra set of bearings for the motor is avoided, thereby reducing complexity and avoiding extra friction and disturbance. In Figure 6-22 the servo motor that has been used is shown.

![Figure 6-22: Brushless servo motor HS03000 [NNEmot]](image)
The length of the magnets is only 10 mm while the total assembly length is 24 mm and the stator outer diameter is 76 mm. The maximum torque of this motor is 6 Nm for short periods of time which suffices for the application [NNEmot]. A further advantage of the brushless servo motor is its durability and controllability. The motor is driven with a digital servo amplifier with sine commutation able to operate in torque and velocity mode [NNCopl]. To measure the speed of the form roll an optical incremental encoder is added with a resolution of 500 lines per revolution [NNUsdi].

6.5 Evaluation of the realized design

The realized design is shown in Figure 6-23. The right hand side of the device will be positioned just outside the working area of the grinding machine, auxiliary functions like the swivel drive box and the fluid supply are located there. The form roll and left hand side extend into the working area. From the right the hydrostatic fluid is supplied and the necessary cables (power and signal of form roll servo, AE signal, pressurized air for seal) are routed towards the form roll drive housing [Derk06].

After realization of the device, parts of the design were evaluated and some revisions made to overcome difficulties. The most important results are discussed in the following sections.

6.5.1 Hydraulic supply system

A supply system for the hydrostatics was created that takes grinding fluid from the machine sump, filters with 2 µm, pressurizes to 3.5 MPa with a screw spindle pump and filters again at 2 µm before supplying the fluid to the bearing. Initially problems where encountered with pollution of the bearing. This pollution led to catastrophic clogging of the bearings. Investigation of the pollution
particles showed that these were zinc-oxides that originated from the high pressure filter and its elements. This was due to the use of zinc plated steel in these parts. The mechanical filtering of the grinding fluid did not pose a problem. Redesign of the filter and filter elements using only stainless steel and non-conductive material to avoid electro-galvanic corrosion solved this problem.

Due to the power of the hydraulic pump the temperature of the fluid rises. As the used grinding machine had no chiller installed, a cross flow heat exchanger was added. The necessity of temperature control is illustrated by Figure 6-24 and shows an approximately linear relation between the temperature of the hydraulic fluid $t_f$ and the vertical Y-position of the form roll, $\delta_Y$. During the experiment the ambient temperature $t_a$ was constant. After addition of the heat exchanger parallel to the high pressure pump the position of the form roll was stable within the measurement accuracy (1 µm).

![Figure 6-24: Influence of hydraulic fluid temperature on radial form roll position](image)

### 6.5.2 Radial system stiffness

The static radial stiffness (load in direction profiling normal force) of the profiling device was measured for different values of the bearing pressure. Based on these results the stiffness of the bearing and the supporting structure of the bearing can be derived. In Figure 6-25 the stiffness measurements are shown. A linear relation between stiffness and supply pressure $p_s$ is expected from the bearing calculations. However these measurements are the stiffness of the total profiling device $C_{prof}$ which consists of the radial bearing stiffness $C_{rad}$ and the stiffness of the structure of the device $C_{struct}$. The bearing stiffness is linearly dependent on the supply pressure $p_s$: $C_{rad} = \zeta_{rad} \cdot p_s$, in which $\zeta_{rad}$ is a bearing constant, leading to:

$$C_{prof} = \frac{1}{\frac{1}{C_{struct}} + \frac{1}{\zeta_{rad} \cdot p_s}} \quad (6-8)$$

This also shows that the relation shown in Figure 6-25 is not linear.
If this is evaluated for two measurements $C_{\text{rad}}$ and $C_{\text{struct}}$ are found to be: $C_{\text{rad}} = 10.7 \cdot p_s \text{ N/µm}$ and $C_{\text{struct}} = 23 \text{ N/µm}$. This leads to a radial bearing stiffness of $37 \text{ N/µm}$ at $3.5 \text{ MPa}$. In Figure 6-25 a line derived from these values is plotted showing its validity. Compared to the calculated radial stiffness of $62 \text{ N/µm}$ (see 6.4.2) the found value is rather low. The explanation for this difference can be found in some deformation of the form roll axis but more important in the deviations of the dimensions of the form roll axis and bushing leading to a larger bearing clearance. This deviation is created after a bearing crash due to pollution (see 6.5.1) and the subsequent polishing (by hand) of the parts. As bearing stiffness is inversely related to the gap height, this directly influences the bearing stiffness.

### 6.5.3 Hydrostatic bearings - dynamic instability

During first operation a problem within the hydrostatic bearing was found: a permanent and audible vibration of the form roll axis. Measurements of the forces showed that the vibration direction was the axial direction. The frequency of the vibration was around $500 \text{ Hz}$. During startup of the bearing the vibrations are extremely loud for a short moment. This could be explained by the air trapped in the system after a stand-still. Air inclusions lead to a high compressibility leading to instability. After a few seconds the air is removed from the system, because at high pressures the air will dissolve in the water, being released again when the pressure drops. However the $500 \text{ Hz}$ vibration of the axial bearing remained present at constant amplitude. Compressibility effects were suspected which was confirmed by the work of Pollmann and Vermeulen in which bearing instability due to the compressibility of the hydraulic fluid is analyzed [Poll89]. These authors derive a design criterion for stability:

$$D_2 = \frac{\rho_{\text{fluid}} \cdot V_{\text{ax,0}}}{A_{\text{ax}}^2 \cdot C_{\text{ax,0}}} \leq 0.5$$  \hspace{1cm} (6-9)
In which $\beta$ is the compressibility of the fluid, $V_{ax,0}$ the volume between the capillary and the lands, $A_{ax}$ the effective area of the bearing and $C_{ax,0}$ the original stiffness of the bearing. Inspection in the design showed that the volume $V_{ax,0}$ consists not only of the pocket volume $V_{ax,pocket}$ but also of the channels in the axis after the restrictor $V_{axis}$, the space behind the thrust disk $V_{thrust}$ and the channels that are needed to connect the axial pressure sensor with the axial bearing pocket $V_{chan}$; these volumes were estimated at: $V_{axis} = 462 \cdot 10^{-9}$ m$^3$, $V_{ax,pocket} = 248 \cdot 10^{-9}$ m$^3$, $V_{thrust} = 283 \cdot 10^{-9}$ m$^3$ and $V_{chan} = 2023 \cdot 10^{-9}$ m$^3$ leading to $V_{ax,0} = 3016 \cdot 10^{-9}$ m$^3$. With the compressibility of water $\beta_{fluid} = 45 \cdot 10^{-11}$ Pa$^{-1}$ [Fine73], $A_{ax} = 4.02 \cdot 10^{-4}$ m$^2$ and $C_{ax,0} = 53 \cdot 10^6$ N/m it follows that $D_2 = 0.45$. As the actual value of $V_0$ is even higher due to simplifications in this estimation this value was considered too high and $V_0$ reduced by 70% by closing off the channel to the axial pressure sensor. This proved effective to remove the vibrations.

6.5.4 Run-out of the form roll axis

To verify the running accuracy of the form roll axis a measurement on the radial displacement of the form roll axis for varying form roll speed was performed. Measurements were done on the form roll axis. The result is shown in Figure 6-26, the measurements where split in two parts: the repeatable run-out (RRO) and the non-repeatable run-out.

![Figure 6-26: Measured run-out of the form roll axis](Image)

The RRO is mainly determined by the form errors on the measurement surface, which explains why the RRO does not vary with frequency. The NRRO will lead to variations in the crushing depth, the limit to these variations was set at 0.2 µm. For the rotational speeds of interest (50-100 Hz) these values are higher. The cause of this increase is not further researched. It is suspected that the running accuracy is compromised by the form errors on the bearing surfaces induced during polishing after a bearing crash.
6.5.5 Force measuring system

As discussed in section 6.5.3 the channels connecting the axial bearing with its pressure sensor were closed off to avoid dynamic instability of the bearing. Therefore the axial measurement possibility was lost. The radial force measurements showed some challenge too. When the signals where evaluated large pressure variations were seen during a rotation (Figure 6-27).

![Figure 6-27: Signal obtained from radial force sensor, $f_s = 1000$ Hz, 4th order low pass filtered with cut-off 300 Hz](image)

This signal is repeatable, the explanation can be found again in the form errors of the bearing surfaces. This can also been seen from the graphs as the 4 large peaks are the rotational frequency of the form roll (67 Hz) and its harmonics. As can be seen from Figure 6-27 the disturbances are an order of magnitude larger than the anticipated profiling normal forces ($F_{nd} < 10$ N). To still be able to measure profiling forces a 1-time-per-revolution index pulse is recorded and added to the force signal. In this way the average force level over one rotation can be measured. The resulting signal contains about 60-70 measurements per second. This signal is used for the results in the remainder of this work. A further disturbance originates from the rotational frequency from the high-pressure pump, this pump runs at 20 Hz, which can also be seen in the zoomed PSD of Figure 6-27. This disturbance could have been eliminated with a differential measurement set-up in which the pressure in two vertical opposing chambers of a radial bearing are both measured. The signal will take the form:

\[
\begin{align*}
    p_{r,1}(t) &= p_{r,av} + p_e \cdot \sin(\omega_{pump} \cdot t) + p_{meas}(t) \\
    p_{r,2}(t) &= p_{r,av} + p_e \cdot \sin(\omega_{pump} \cdot t) - p_{meas}(t) \\
    p_{r,1}(t) - p_{r,2}(t) &= 2 \cdot p_{meas}(t)
\end{align*}
\]  

(6-10)

In which $\omega_{pump}$ is the pump frequency, $p_{r,1}$ and $p_{r,2}$ the pressures in the two opposing chambers and $p_{meas}$ the pressure variation that exists in the chamber in reaction to the external force. From the differential signal, $p_1 - p_2$, the harmonic component from the pump is removed improving the signal to noise ratio. In the present realization this could not be changed and the signals are filtered to
suppress the influence of the pump frequency. As the signals are only used for quasi-static measurements in the rest of this work, the influence of this filtering operation is acceptable.

### 6.5.6 Adjustment system

The radial adjustment system was used together with a measuring tool to ensure that the swivel block was moved horizontally. Practice showed that with the coarse alignment bolt a resolution of 2 µm could be achieved. The fine-adjustment proved to work but was not used further. To avoid the difficulties associated with the double guide in the current concept an improved concept is suggested and presented in Figure 6-28, which makes use of elastic hinges and only a single adjustment axis. The bearing block is rotated around the z-axis when the adjustment axis is moved upward. The centre of rotation is at the elastic support of the supporting swivel bearing. To achieve a displacement of 5 mm at the form roll a travel of about 10 mm is needed in the adjustment axis, leading to a rotation of the supporting swivel bearing of about 2 degrees.

![Figure 6-28: Proposed improvement for radial adjustment system](image)

### 6.6 Summary and conclusion

Based on an analysis of available form profiling systems and the situation demanded by end-users a list of requirements was established. This list is translated into a list with design requirements and design solutions for the identified functions. This has led to a conceptual design that is further detailed and has eventually resulted in the production of the profiling device. The device was evaluated on some critical points and improved where possible. Some improvements for a next version are suggested as they could not directly be implemented in the current version. The main suggested improvements concern the radial adjustment system and the force measurement system.

The developed system meets the requirements set out in the beginning of the chapter, although the system stiffness is lower than calculated due to manufacturing tolerances. In the next chapters the profiling device will be used to crush profile diamond grinding wheels.
7 Form roll synchronization

7.1 Introduction
In the previous chapter the development of the dressing device has been introduced. With this design stiffness, damping, accuracy and kinematic functionality are taken care of. In this chapter the key factor for form crushing: synchronization of the form roll and grinding wheel circumferential speeds is discussed.

The basic characteristic of the crushing process is to remove grinding wheel material by applying a normal force only to the grinding wheel, thereby creating brittle fracture of the bond system. A relative speed between the grinding wheel and the form roll (slip) is therefore not needed. When the wear of the form roll is considered this wear is, for a given combination of grinding wheel and form roll, related to the slip distance. Avoiding a relative speed between the two bodies, called synchronization, aims to minimize this slip distance and therefore wear of the form roll. The wear mechanisms involved are discussed in section 7.2. In 7.3 the current state-of-the-art in synchronization of the form roll and grinding wheel speed is discussed. In section 7.4 a new synchronization concept is introduced based on a torque balance of the form roll.

7.2 Form roll wear and slip
Due to the nature of the dressing process (material removal) and the contact bodies (especially the grinding wheel as it has, by its nature, an irregular surface) some slip will always be present in the contact point. This slip is difficult to quantify and cannot easily be influenced. This slip will be referred to as micro slip while the slip due to a mismatch of the average circumferential speed of the two bodies will be referred to as macro slip.

Micro slip
A closer look at the contact point shows that there are several effects that will lead to micro slip. In Figure 7-1 these effects are illustrated. As a starting point the bodies are assumed to have perfectly round surfaces.
Reynolds slip is caused by the fact that the arc length a-b (see Figure 7-1a) of the contact of bodies A and B changes in the contact zone due to the deformation of the contact bodies [Beek04]. In the special case that both bodies have the same geometry (diameter) and stiffness no slip will occur as both bodies will undergo the same strain. In other situations the two materials in the contact zone will experience different strains and therefore need to slip.

Heathcote slip is caused by the differences in rolling radii in the contact zone. In Figure 7-1b the situation is strongly exaggerated. The circumferential speeds of the bodies is equal at radius $r_{A,av}$ and $r_{B,av}$ and is defined by $v_{av}$. At $r_{A,max}$ on the other hand the speed of body A will be higher and of body B lower than $v_{av}$.

A third micro-slip component is caused by the fact that grinding wheel material is actually deformed and fractured in the contact point. In Figure 7-1c the fracture zone is indicated. Body A is regarded here as a form roll and B as the grinding wheel. The arc length c-d defines the contact zone. It can be seen that a point on body A moving from point c to point d will displace radially into body B. When considering the actual crushing process, this process will lead to dislodging and displacing of diamond grains when they are in contact with the form roll, resulting in micro slip between the two bodies.

As a last remark it has to be noted that the grinding wheel cannot be considered as a perfectly round cylindrical surface and that the contact situation will be irregular and intermittent. This can be understood from figure 3.6. The contact pressures of the diamond grains contacting with the form roll will be high due to the localized contact.

Lubrication might lower the friction coefficient in the contact point and thereby reduce the friction forces and therefore wear at a given normal force. The influence of reducing the friction coefficient in the contact zone will be studied in more detail in section 7.4.1.
Macro slip

Macro slip is defined as the difference in average surface speed of the two bodies. For the situation in form crushing where there exists a certain depth of cut this would implicate the use of an average diameter on which the speeds of the two bodies have to be evaluated. In Figure 7-1b this is illustrated and the difference in speed at \( r_{a,v} \) and \( r_{A,v} \) is defined as macro slip. Macro slip is also what is addressed in dressing operations by the speed ratio \( q_d \). A speed ratio of 1 defines the absence of macro slip and is the aim in crushing. In other mechanical dressing operations macro slip is deliberately introduced to remove material (by a grinding action). The situation where no macro slip exists will be referred to as the synchronized situation.

Form roll wear

Wear at the interface of two bodies can in general be classified in four wear mechanisms: adhesive, abrasive, corrosive and surface fatigue. The main contact between the two bodies is diamond on diamond. In this situation adhesion can play an important role [Feng91], [Tzern93]. The effect of adhesion between diamonds can strongly be reduced by lubricating the contact with water, adhesive forces can be reduced by a factor 3 to 4. Oil as a lubricant shows no improvement as compared to sliding contact in air [Feng91]. A second material combination is the binder material of the grinding wheel on the diamond form roll. But because these are clearly different materials adhesion is not expected to be a significant problem. Corrosive wear is unlikely as the involved materials are relatively inert at room temperature and the temperatures in the contact zone will not rise significantly during crushing. The importance of surface fatigue is very dependent on the type of material used. It is unlikely to occur in CVD diamond as investigated by Davies et al. [Davi04]. Polycrystalline diamond (PCD) is however sensitive to fatigue wear [Lin92] but not used very often for (crush) form roll applications nowadays due to the availability and reduced price of CVD diamond [Hess07]. Abrasive wear can therefore be expected to be the dominant wear mechanism for this contact situation and then especially abrasive wear due to the contact of diamond on diamond. This is also mentioned by Hayward as the primary wear mechanism of diamond [Hayw91].

Abrasive wear is a mechanical wear process due to the sliding motion between bodies. In this process material in the contact area is deformed (first elastically and later plastically) which can lead to material removal from one of the bodies. The harder and smoother the surfaces of the bodies are, the smaller will be the abrasive wear. Wear is also related to the (sliding) forces in the contact zone.

In short reduction of wear of the form roll during crush dressing would demand for:

- A hard surface of the form roll.
- A low roughness of the form roll.
• Reduction of (sliding) forces.
• Avoidance of sliding motion between bodies.

In dressing operations generally diamond is used for the form rolls, which has already the highest hardness known. The roughness of the form roll should be as small as possible; a continuous diamond surface that can be achieved with full CVD diamond rolls might be advantageous here. This is confirmed by the results of Hessel [Hess03], were SEM micrographs of a CVD diamond form roll show a low roughness. The roughness of the grinding wheel will be very high due to its function (abrasive material removal) and is not considered as a parameter that can be influenced. The sliding forces in the contact zone can be reduced by lubrication; this also affects the wear generated by the aforementioned micro-slip. Lubricating can be done by applying water as is further explained in section 7.4.1. The avoidance of slip between the two bodies is the parameter that can be influenced most to avoid wear. The next sections will deal with the reduction of slip in the contact zone between form roll and grinding wheel.

7.3 Speed controlled synchronization

The problem of synchronizing the circumferential speeds of the form roll and the grinding wheel has been studied by Hessel [Hess03]. In this research it was concluded that a free running form roll, as used in profile crushing, brought into contact with a grinding wheel rotating at a constant speed $v_{sd}$, will accelerate towards this speed $v_{sd}$, eventually satisfying $v_{sd} = v_{rd}$. In form crush dressing this will not be sufficient because:

- The contact area, and therefore the friction force in the contact area that drives the form roll, is too small to overcome the friction in the bearings of the form roll axis.
- In contrary to profile crushing, form crushing is an intermittent process and every time contact is lost the speed of the form roll decreases and has to be accelerated when contact is established again, resulting in a slip phase.

In profile crushing, where a roll with the total grinding wheel profile is used, the contact area is larger, the speed is much lower (typically 1-2 m/s) and the contact is not lost as the grinding wheel is only fed radially into the wheel.

It was therefore concluded that an active drive system is needed for the form roll. Hessel studied several drive concepts:

- An air driven system that was only meant to reduce the acceleration phase by creating an initial speed before contact, shortening the slip phase.
- An electrically driven open loop speed controlled system.
- An electrically driven closed loop speed controlled system.

The first system showed a bad synchronization behavior along a profile, the system was not optimized further and tests were continued with the electrically driven system. A schematic overview of this system is shown in Figure 7-2.
Figure 7-2: Velocity based synchronization system as proposed by Hessel

The rotational speed of the grinding wheel, $n_{sd}$, is measured and fed back to the control system. Furthermore the distance between the grinding wheel and form roll axes, $\Delta a$, is measured continuously. The diameter of the form roll, $d_r$, is once measured and assumed constant. With this information it is possible to calculate the needed rotational speed of the form roll, $n_{rd}$.

Although the velocity controlled system should be able to achieve synchronization it depends fully on the accuracy and correctness with which the speed of the form roll can be calculated and controlled. Among others this is dependent on the accuracy of: the measured diameter of the form roll $d_r$, the axis distance $\Delta a$, and the rotational speed of the grinding spindle $n_s$. Furthermore the performance of the control system will have an influence.

Assuming some values for these errors will give an indication of the performance of the present system. An error for $\Delta a$ of 0.02 mm will lead to a wrong estimate of the grinding wheel diameter $d_s$ which is assumed to be 70 mm, by 0.04 mm (0.057%). The form roll diameter $d_r$ assumed to be nominally 100 mm, can in practice be measured with an accuracy of about 0.01 mm (0.01 %). The wear of the form roll also leads to a wrong estimate of the diameter $d_r$ and varies from 0 to 0.2 mm (0.2%, 0.1 mm radial wear is taken here as the wear limit). This can lead to a speed error of up to 0.27%. Assuming dressing is performed at grinding speed, typically $v_s = 25$ m/s, this leads to speed variations of up to 0.067 m/s. This value in itself does not seem to be that high compared to the actual surface speed. However the fact that the system is velocity controlled implies that the system is enforcing a slip condition and thereby wear, which is against the very nature of the system.

Apart from the difficulty to actually calculate the correct speed for the form roll, this system also asks for operator intervention (measuring the diameters) and measuring the axis distance $\Delta a$. This distance measuring is in industry (currently) implemented by installing an extra measuring device.
that is costly and most of all, unpractical. In principal this function should be integrated into the machine tool control employing the available measurement systems. This would remove the unpractical extra measurement device but the cost involved would remain (especially for retrofit situations). Furthermore an extra interaction with the machine tool control is introduced.

The control of the form roll should be able to achieve and maintain the prescribed speed accurately. The performance of the control system of the form roll will influence the synchronization quality. In earlier research the performance of the control system has limited the results, especially at higher crushing speeds [Hess04].

The goal of the next sections is to design a control system for the form roll that:

- Guarantees synchronization independently of the measuring errors mentioned above.
- Does not need operator intervention.
- Has no need for external measurement devices.
- Can operate without interaction with the machine tool control.
- Performs well at higher speeds.

### 7.4 Torque controlled synchronization

This section proposes and validates a synchronization principle based on a torque control. The discussion will be started by taking a closer look at the actual contact zone between grinding wheel and form roll. After that a torque balance is derived for the form roll system. On basis of this the limits of synchronization are established and a control strategy is derived on basis of these limits.

#### 7.4.1 Friction in the contact zone

To understand the behavior of the synchronization process a closer look is given at the contact zone of the crush form roll and the grinding wheel. Basically two bodies are brought into contact while rotating. In the contact zone a tangential force can be transferred, assuming a friction constant larger than zero. This tangential force is related to the normal force via:

\[ F_t = \mu \cdot F_n \]  

In here \( F_n \) is the normal force in the contact zone, \( F_t \) is the tangential force and \( \mu \) is the friction coefficient. This relation describes only the magnitude of the forces. Friction behaves in such a way that it always opposes the force or motion (= relative speed in contact zone) that causes it. Furthermore a friction coefficient is defined for the static situation, \( \mu_s \), where there is no motion between the contact bodies and the dynamic situation, \( \mu_d \), where there is a relative speed (slip) between the contact bodies. In general the static friction coefficient is different from the dynamic; mostly \( \mu_s > \mu_d \). This is illustrated in Figure 7-3 for a body \( M \) that is pressed onto a surface by a force \( F_n \). Due to a static force \( F \) or a motion \( v \) a resultant friction force \( \mu F_n \) is developed. Mostly \( \mu_s \).
is also (lightly) dependent on speed but as the slip speeds are low in this application this influence is discarded.

\[ \mu \frac{F_n}{F} \]

Following this an estimate of the friction coefficient and the normal force in form crushing would give the magnitude of the synchronizing force \( F_t \). The normal forces in crushing are between 2 and 10 N, typically 5 N for the top radius of the dresser and grinding wheels used (see also chapter 8 and 9). The friction coefficient is a more difficult parameter. In theory the contact is diamond on diamond with a water based grinding fluid as lubricant. The roughness of the grinding wheel is such that conventional friction tests do not apply as they are performed with smooth surfaces. For these smooth surfaces Feng and Field [Feng91] determined that the friction coefficient of diamond sliding on diamond is about 0.05 to 0.15 (this is valid for situations where there is moisture available in the air that can interact with the surface, above 100 °C the friction coefficient will rise sharply). This is also confirmed by Tzeng [Tzen93] who reports even friction values as low as 0.001 at very low sliding speeds and with water as a lubricant.

The effective synchronizing torque, \( T_{sync} \), that is developed can be described by:

\[ T_{sync} = \frac{d_r}{2} F_{td} - \frac{d_d}{2} \mu_d \cdot F_{nd} \tag{7-2} \]

If slip is present the dynamic coefficient of friction has to be used, if not the static is to be used. Furthermore when slip is present the magnitude and direction of the forces are known. In the absence of slip only the maximum of the friction force can be determined and the direction can be anywhere in the plane of contact, depending on the direction of the other forces present:

\[
T_{sync} = \begin{cases} \frac{F_{nd} \cdot \mu_d \cdot d_r}{2} = T_{sync,s,max} &: \nu_{rd} = \nu_{sd} \\ \frac{F_{rd} \cdot \mu_d \cdot d_d}{2} = T_{sync,d,max} &: \nu_{rd} \neq \nu_{sd} \end{cases}
\tag{7-3}
\]

This means that when there is synchronization a certain torque, \( T_{sync,s,max} \), can be transferred in the contact point before slip will occur. In other words: in a certain range this torque can avoid deceleration or acceleration of the roll, maintaining synchronization. Normally the static coefficient

---

---
is higher than the dynamic coefficient leading to a higher \( T_{\text{sync},\text{d},\text{max}} \). Because the actual values are unknown the rest of the text will assume one single friction coefficient, \( \mu_s = \mu_d \) and therefore:

\[
T_{\text{sync},s,\text{max}} = T_{\text{sync},d,\text{max}} = T_{\text{sync},\text{max}}
\] (7-4)

### 7.4.2 Torque balance of the form roll system

In the previous section it has become clear that during contact between a form roll and a grinding wheel there is a torque that will act in such a way that it accelerates (or decelerates) the form roll towards the synchronized speed. In this section the other torques acting on the form roll system are studied.

There will be a torque developed by the form roll drive system; in this case the servo motor that drives the form roll axis: \( T_m \). This torque is determined by the servo controller and can be influenced. The total form roll axis will have a certain friction; this is defined by the form roll friction torque \( T_f \). This torque is determined by the system design and will be further discussed in section 7.4.3. The crushing process itself will also lead to a friction torque, which can be seen as a sort of rolling friction, compared with a car wheel driving through loose sand, this is therefore described by \( T_r \). This torque will be dependent on many parameters: specification of the form roll and grinding wheel, form roll geometry (especially top radius and wear flat), depth of cut in dressing, dressing speed, dressing feed, and lubrication. \( T_r \) will be considered as given and unknown. The torque will however always be directed opposite to the direction of motion of the form roll. There will always be some external influences that will have an effect on the form roll speed and these are indicated by \( T_{\text{ex}} \). An example of such an influence (and the largest in practice) is the grinding liquid that is used during the dressing process. This fluid will interact with the roll and thereby create a significant disturbing torque. A last torque acting on the roll is defined by the dynamics of the system: to de- or accelerate the form roll an extra torque \( T_a \) is needed. \( T_a \) is defined by:

\[
T_a = I_r \cdot \frac{2 \cdot V_d}{d_t}
\] (7-5)

In this equation \( I_r \) is the mass moment of inertia of the form roll system.

For the form roll system the torque balance can now be written as follows:

\[
T_m + T_{\text{sync}} = T_f + T_r + T_{\text{ex}} + T_a
\] (7-6)

To increase understanding of the system the friction torque of the form roll system, \( T_f \), will be studied in more detail in the following section. The discussion of the influence of the system dynamics is postponed till section 7.6 and for now \( T_a \) is considered to be zero.
7.4.3 Torque-speed relation

The bearing system of the form roll should ideally be frictionless. Unfortunately this is not possible. As explained in chapter 6 the form roll is supported by a hydrostatic bearing which is characterized by a friction torque increasing linearly with speed. Measurements were made on the speed-torque relation of the form roll system and are shown in Figure 7-4. $T_{fr}$, $T_{ax}$ and $T_a$ were set to zero.

This curve can be represented by a quadratic equation:

$$T_m = A \left( \frac{2 \cdot v_{rd}}{d_r} \right)^2 + B \left( \frac{2 \cdot v_{rd}}{d_r} \right) + C \quad (7-7)$$

The linear relation of speed and torque (B) is the Newtonian fluid friction of the bearing. Furthermore there exists a static friction component (C) which can be contributed to the use of a rubber contact seal to prevent water from entering the motor compartment. The light quadratic influence (A) can be contributed to the presence of air drag of the rotor of the electromotor and the form roll.

![Figure 7-4: Speed-torque relation of the form roll drive system](image)

Basically the graph shows that at a given torque the form roll will achieve a certain speed. In other words to vary the speed when the torque on the form roll system is given, an extra torque is needed.

7.4.4 Form roll synchronization concept

To improve the quality of synchronization a new concept is proposed in which the form roll will actually self-synchronize making use of the synchronizing torque, $T_{sync}$. The basic idea is that the form roll is not driven in a velocity controlled way, but by torque control. When the achieved speed of the form roll does not match the speed of the grinding wheel, the roll will accelerate automatically towards the synchronous speed. To illustrate this, an experiment is performed in
which the form roll is driven with a constant torque. This torque is chosen such that the speed of the roll, \( v_{rd} \), is roughly 0.5 m/s lower than the grinding wheel speed, see Figure 7-5.

In this figure two dress passes are performed, dressing a straight profile on the grinding wheel by traversing it with the form roll. The initial roll speed is too low (about 24.9 m/s). At about \( t=25 \) s. contact is made between form roll and grinding wheel. Quickly the speed of the form roll changes to roughly 25.4 m/s. At about \( t = 80 \) s contact is lost and the speed of the roll lowers, however before the roll is stable at its idle speed, contact is established again in the second dressing pass. After this pass the roll returns to its idle speed.

This experiment shows that the crushing process itself can actually change the speed of the form roll. Effectively the torque control creates zero “stiffness” towards speed changes in the working point. However the achieved speed is lost when contact is lost because then \( T_{sync} \) is not present.

As a next step it needs to be verified if the speed that is reached during contact is actually the synchronous speed, \( v_{sync} \). For this purpose an experiment is set up in which the form roll is given different initial speeds represented by a deviation of the synchronous speed \( \delta \). This is realized by controlling the torque of the drive system. The results are shown in Figure 7-6. In this case use is made of a form roll that has a wear flat of \( b_d = 150 \) µm, the grinding wheel is for this experiment a Silicon Carbide crushable wheel (Winterthur 11C 250/350 F/G20 VP030G), average grain size of around 50 µm. In these experiments no grinding fluid is used, to reduce the influence of \( T_{ex} \). As can be seen a speed mismatch, \( \delta = v_{rd} - v_{sd} \), of below 1 m/s synchronizes quickly.
It can also be seen that $v_{\text{sync}}$ is independent of the sign of the speed deviation (above or below $v_{sd}$), indicating that the achieved speed is actually the synchronous speed. However if the speed difference is too high (in this particular situation found to be: $v_\delta = 2.97$ m/s) the form roll only accelerates towards the synchronized speed but a permanent slip condition remains. Therefore there is a limit to the amount of self-correction that the process can achieve. For self-synchronization the following should be satisfied:

$$|T_\delta| = |T_m - (T_T + T_{sd})| \leq T_{\text{sync,max}} \quad (7-8)$$

In here the mismatch between all disturbing torques excluding $T_{\text{sync}}$ and the torque generated by the servo motor, $T_m$, is represented by $T_\delta$. Therefore to achieve self-synchronization this mismatch cannot be allowed to be higher than the torque that can actually be transmitted in the point of contact, $T_{\text{sync}}$.

If Equation 7-8 does not hold, synchronization will not be fully achieved and slip between the form roll and the grinding wheel will be present resulting in increased wear of the system, with the associated negative influence on accuracy and economy.

Based on Equation 7-8 a system can be proposed that will keep the speed deviation, $v_\delta$ small. This would be possible by using the speed-torque curve and looking up the torque needed to achieve
the needed form roll speed. This system is illustrated in Figure 7-7. This method was introduced in [Derk07].

![Figure 7-7: Torque control with look-up table](image)

The basic principle is that the controller will start up based on the average grinding wheel speed entered in the grinding machine control. Based on this value a torque is calculated. When dressing the speed will most likely be a little different, however the achieved speed is fed back into the system and a new torque value will be calculated, based on the relation sketched in Figure 7-4.

There are several limitations to this system: first of all the speed-torque curve is assumed to be fixed. This is not the case. Measurements have shown that the curve is dependent on the properties of the used fluid in the bearing (age, concentration, viscosity and temperature among others). Furthermore the external torque $T_{ex}$ is not taken into account while it can have a significant influence. A third and more fundamental disadvantage is that this system is unstable when contact with the grinding wheel is lost: in that case the smallest disturbance in the speed can result in an unstable behavior of the system, resulting in a continuously increasing or decreasing torque.

However the idea to, roughly, determine the speed while principally operating in torque mode to achieve synchronization, can be achieved in another way. To do this a signal is added that will indicate whether there is contact between the form roll and the grinding wheel or not. The AE (acoustic emission) sensor available in the system is fit for this purpose. With this signal two different strategies can be followed for the contact and no-contact situation. The following system is proposed: when starting up the system a velocity control system is used to accelerate the form roll to its initial speed (the nominal speed of the grinding wheel). When dressing is started and contact is established (detected by the AE sensor) the control system will switch to a torque controlled mode. After loosing contact the velocity control will take over again. The set-points for the torque and velocity controllers have to be defined in the preceding stage: when there is contact the form roll will change its speed, this speed is recorded in a memory. When contact is lost the velocity control will use this value as set-point. In the same way, during velocity control the average torque is recorded to a memory that will be used when the system switches back to torque control. This system is illustrated in Figure 7-8. It does not need a look-up table as it needs no prior knowledge of the system behavior. It also deals automatically with variances and disturbances ($T_{ex}$). Finally the system is stable when there is no contact because speed is simply maintained constant.

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7.5 Experimental validation of torque based synchronization

The system proposed in the preceding section has been realized and tested. Used were, beside the dresser, AE sensor and servo controller, a desktop computer with a data acquisition card on which the suggested control strategy has been implemented (see chapter 5). The servo controller remained in torque control mode as this controller does not allow changing from torque to speed control during operation. To enable fast switching between the control modes, based on the acoustic-emission sensor, the velocity control has been implemented on the desktop computer. The update rate of the achieved speed control is relatively low with 25 Hz. However for this system it suffices. The torque controller implemented in the servo controller has a much higher update rate of 20 kHz.

The memories as indicated in Figure 7-8 are implemented with a filter to calculate the average speed and torque and reduce the influence of noise. In Figure 7-9 the result of this system is shown.

The form roll is given a speed error $\delta$. During the first dressing pass the form roll speed directly accelerates to the grinding wheel speed. However due to the influence of the implemented filter,
the average recorded speed is lower than the synchronized speed. During every next pass this error is reduced. For this experiment the filter was made to act “slow” to visualize the convergence of the system. In the figure it becomes clear that after a few passes the torque and speed values are so well adapted that it becomes difficult to discriminate in the speed signal between contact and non-tact, indicating an optimal synchronization process.

7.6 Synchronization on profiled grinding wheels

Up to now only straight profiles have been used. This means that the torque \( T_s \) has been zero as there is no speed variation along the profile. In this section the influence of an actual profile with varying radius \( r_s \) and therefore \( v_{rd} \) along the profile is studied.

Recalling Equation 7-5:

\[
T_s = I_r \left( \frac{2 \cdot v_{rd}}{d_r} \right) = \frac{2 \cdot I_d}{d_r} \cdot v_{rd}
\]  

(7-5)

It is seen that the value of \( T_s \) is influenced by the speed rate of change on the one hand (a process parameter) and the mass moment of inertia over the radius (a design parameter).

Therefore in the system design phase \( 2 \cdot I_d/d_r \) should be kept low. The parts with the largest diameter have most influence. This will be the form roll. In future applications it is therefore interesting to optimize the form roll geometry to this respect. In present form roll designs this has not been an issue, as the dynamic performance does not play a role in other dressing operations.

The speed rate of change \( \dot{v}_{rd} \) is determined by several factors: the radius of the grinding wheel, \( d_r/2 \), the feed speed along the profile, \( v_{fd} \), decomposed into the axial feed speed, \( v_{fad} \), the angle the profile makes with a straight profile, \( \beta \) (see Figure 7-10) and the nominal grinding wheel speed, \( v_{sd} \).

In practice for a certain grinding operation, the grinding wheel diameter and profile are given. The grinding wheel speed is determined by the grinding process and dressing should preferably be performed at the same speed (\( v_s = v_{sd} \)). Therefore the feed speed, \( v_{fd} \), is the only parameter that can be used to influence \( T_s \). However this will influence the overlap ratio \( U_d \) and profiling time and should be considered.

Now Equation 7-8 can be extended to formulate the demand for synchronization on profiled grinding wheels:

\[
|T_d| = |T_m - (T_f + T_e + T_{dyn})| \leq T_{sync,max}
\]  

(7-9)

This shows that, using the system described in 7.4.4, the acceleration torque \( T_a \) can never be larger than \( T_{sync,max} \).
In practice it will even be smaller because $\left| T_m - (T_r + T_d + T_{ed}) \right| > 0$ due to the variations along the profile for which the control system does not compensate. As $T_{sync,max}$ cannot be estimated easily an experiment is set up to study the synchronization along a profile. The parameters used are given in Table 5 below.

<table>
<thead>
<tr>
<th>$v_{rd}$</th>
<th>25 m/s</th>
<th>Grinding wheel</th>
<th>D46-V+2646-J-8-C100-23</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_d$</td>
<td>2</td>
<td>Form roll</td>
<td>Arranged CVD diamond</td>
</tr>
<tr>
<td>$\beta_{max}$</td>
<td>45°</td>
<td>$d_r$</td>
<td>120 mm</td>
</tr>
<tr>
<td>$a_{rd}$</td>
<td>1 µm</td>
<td>$d_s$</td>
<td>70 mm</td>
</tr>
<tr>
<td>$b_s$</td>
<td>8 mm</td>
<td>$R_{top}$</td>
<td>100 µm</td>
</tr>
</tbody>
</table>

Table 5: Parameters used in profile crushing with torque control system

These values will lead to a high $v_{rd}$ and therefore a relatively extreme experiment is performed. The profile to be dressed is shown in Figure 7-11 below.

A top radius of $R_{top} = 100$ µm is used. This is relatively small resulting in a small transferable torque $T_{sync,max}$. The used grinding wheel had a D46 grain size with medium hardness and porosity. This leads, as will be shown in chapter 9, to relatively low normal forces leading in its turn to a reasonable $T_{sync,max}$. 

Figure 7-10: Definition profile angle and profiling parameters
The results of this experiment are shown in Figure 7-12.

At time 0 contact is made with the grinding wheel. At this moment the speed of the roll quickly increases to the synchronized speed of about 25.1 m/s. When the form roll proceeds into the profile the radius of the grinding wheel becomes smaller and the speed has to decrease, this happens e.g. a little after 1 s. The profile can be recognized in the speed profile (inverted) when comparing Figure 7-11 and Figure 7-12. On the places where there are external corners on the profile, the form roll loses its contact with the grinding wheel. This is due to the fact that these corners are programmed as sharp corners while there will effectively be a finite radius. Therefore the contact with the grinding wheel is lost momentarily. Consequently there is no AE signal and the controller changes to velocity mode. The speed value in the memory will not exactly match the speed at that moment due to the changes along the profile and the effect of the used filters. This explains the somewhat odd speed variations at these positions.

When the highest points and the lowest points in this speed graph are compared the speed difference can be compared to the speed difference expected from the contour variations. This showed that full synchronization was achieved along the complete profile.

### 7.7 Conclusion

In this chapter synchronization of the form roll was studied. The shortcomings of the existing systems were discussed and the basic behavior of the process investigated. Based on this a new
synchronization system is suggested implemented and validated that is able to synchronize the form roll to the grinding wheel speed. The system demonstrated to work on profiled grinding wheels, furthermore it is robust and does not need any additional measuring or human intervention, as opposed to existing systems, easing integration onto existing machines.
8 Process design

8.1 Introduction
In the previous chapter a control system for the form roll was developed with the goal to achieve optimal synchronization and thereby reduce wear of the form roll. This chapter deals with the control of the wear of the dress-roll to secure a consistent high-accurate grinding wheel profile. The wear of the form roll can be influenced by choosing the form roll material. Furthermore the absolute wear of the form roll is not the only relevant parameter. When the form roll can easily be reshaped, its wear becomes less problematic. In this chapter the use of different materials for the form roll is investigated (section 8.2). Based on the results the regrinding of the form rolls on the machine is studied both from an economical (8.3.1) as well as a technical perspective (8.3.2, 8.3.3, 8.3.4). In section 8.4 an effort is made to calculate the in-process radial form roll wear. This is an unknown value in all form dressing operations and a method is proposed that can be implemented with the developed form crushing system.

8.2 Form roll material selection
The form roll is the tool in the diamond profiling process and its wear can be considered as the main cause for profile inaccuracies. In chapter 6 it was motivated that regrinding of the form rolls on the machine is required. As regrinding will take a certain effort too, there has to be a balance between the wear resistance during crushing and the regrindability of the form roll. An experimental study has been performed to determine the wear of various candidate form roll materials and their regrindability. Hardened steel has been used by Geisweid who used hardened X210Cr12 tool steel having a hardness of 62-64 HRC [Geis80]. Barnard recommends a M42 (UNS T11342) tool steel hardened to 66-68 HRC [Barn89b]. The use of tungsten carbide based hardmetals for profile crushing rolls has also been documented [Barn89b], [NNWint], however its use is associated with clogging of the grinding wheel surface but no explanation for this phenomenon is given [Barn89b]. Harbs used both hardened steel and tungsten carbide form rolls for form crushing but unfortunately no results were presented on the difference between these two materials and the measured wear [Harb97]. Therefore hardened steel and hardmetal are both included in the tests. Chrome is often used as wear resistant layer because of its hardness and abrasion resistance, it is also a relatively cost-effective coating that can be applied in layers up to 1 mm. Chrome coated steel rolls are therefore included in the test. A D46 grain size bronze-cobalt
bonded diamond grinding wheel is included in the test as this type of tool is used in form dressing of conventional grinding wheels. As a reference a dedicated form crushing roll made of arranged polycrystalline CVD diamond rods, as described in chapter 5, is included. Soft steel rolls are also mentioned to be useable [NNWint], however at the cost of increased wear. A plain steel roll was included in the test. For the materials used the hardness is given in Table 8-1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Hardness</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>25 HRC</td>
<td>Plain steel</td>
</tr>
<tr>
<td>Hardened steel</td>
<td>62 HRC</td>
<td>Through hardened</td>
</tr>
<tr>
<td>Chrome</td>
<td>70 HRC</td>
<td>Chrome layer on soft steel core</td>
</tr>
<tr>
<td>Tungsten carbide based hardmetal</td>
<td>1400 HV30</td>
<td>G13, 8.5% cobalt, 2-4 µm grain size</td>
</tr>
<tr>
<td>D46 metal bonded diamond wheel</td>
<td>Diamond: HK 57 - 104 GPa</td>
<td>Soft cobalt-bronze binder material, concentration diamond C150</td>
</tr>
<tr>
<td>Arranged diamond rods</td>
<td>CVD diamond: HK 81 GPa</td>
<td>CVD diamond rods: 0.8 x 0.8 x 5 mm.</td>
</tr>
</tbody>
</table>

Table 8-1: Hardness of used form roll materials

The goal of the experiment was to compare the different form roll materials on their suitability for form crushing. The experiment consisted of form crushing a straight profile on a vitrified diamond grinding wheel with average grain size of 46 µm, concentration 100 (D46-V+2646-J-S-C100-23, see chapter 9 for details). For all rolls crushing was performed until a radial wear of about 20 µm was achieved. The crushing parameters used where: \( v_d = 25 \text{ m/s} \), \( a_d = 1 \text{ µm} \), \( U_d = 2 \).

Form roll wear for different form roll material

![Figure 8-1: Wear ratios for different material of the form rolls](Image)
As a result the relation between the volume removed from the grinding wheel and the wear volume of the form roll (the $G_d$ ratio) is calculated and used to compare the different materials. The results are shown in Figure 8-1.

Figure 8-2: wear surface of 4 different form rolls
In Figure 8-2 the used surfaces of 4 different form rolls are shown. The images are created with a confocal microscope. The upper figure of every set is a purely confocal image. The lower figure combines light microscopic information with the confocal data, giving more information on the surface texture. The extreme wear of the mild steel form roll is not only due to abrasive wear, as can be seen from Figure 8-3. Shown is a print of the form roll wear profile made by gently traversing a piece of graphite. With a dotted line the original contour of the fresh form roll is shown. Material of the form roll (in white) extending outside (below) the contour is seen. This is explained by plastic deformation of the form roll resulting in a burr on the sides. Clearly plastic deformation can be a significant wear mechanism of the form roll if the roll material is chosen too soft.

*Figure 8-3: Wear profile of the mild steel form roll replicated in graphite after \( a_{\text{tot}} = 50 \, \mu m \)*

The hardened steel roll performed comparatively well. With a measured \( G_d \) ratio of 75 this material ranks highest after the arranged CVD diamond crushing roll. Even though the tungsten carbide roll is harder than the hardened steel roll its performance is considerably lower. Both rolls show no or insignificant plastic deformation, see Figure 8-2, what can be seen from the straight edges of the wear flat. The same can be said for the chrome roll. Even though chrome has a high abrasive wear resistance the \( G_d \) ratio is very low, indicating another wear mechanism than abrasive wear. When the surface of the chrome roll is studied more closely (Figure 8-4) a typical pattern with sharp lines can be seen.

*Figure 8-4: Detail of chrome roll wear surface*
These lines are cracks that are formed in the layer during the plating process. The high hardness of the layer combined with the cracks make the layer susceptible to fatigue wear. During crushing the loading of the surface is cyclic, resulting in crack growth leading eventually to chrome particles breaking out of the surfaces. This explains the high wear of the chrome roll.

The D46 metal bonded diamond roll showed such a high wear that the diamond particles seemed to have no (positive) influence. The explanation for this behavior becomes clear from Figure 8-2 where the edges of the wear flat are clearly not straight, indicating plastic deformation, just as the soft steel roll. Graphite prints confirmed this. The bond material of this roll is responsible for this behavior. The material in the contact zone is loaded in compression, supported by the body of the roll and restricted by the grinding wheel. When the stresses are sufficiently high and the material ductile enough the material will flow to the sides. The diamonds are simply pushed into the form roll by the grinding wheel and do not contribute to the wear resistance.

The hard metal used for the full hard metal form roll was of low cobalt content. This results in a higher hardness at the cost of increased brittleness compared to an average tungsten carbide material. It was therefore expected that the low performance of the hard metal roll was caused by crack propagation and the breaking out of particles out of the roll surface. A closer look at the wear surface, Figure 8-5, does not support this hypothesis; however brittle fracture might be present at the grain level. The peaks observed on the surface have a different texture indicating that these are material adhesions. These adhesions are also observed on the hardened steel roll, but could not be observed on the other rolls. Most likely material is embedded in the softer rolls.

![Figure 8-5: Detail wear surface of the hard metal form roll](image)

The hardened steel form roll showed no fracture and very little plastic deformation, see Figure 8-2, indicating a good balance between toughness and hardness and explaining the good performance.
The form crush roll made of CVD diamonds shows an interesting behavior, Figure 8-6, the diamonds have wear flats, showing neither fracture nor deformation, however the bond material that holds the particles in their position shows a little plastic deformation. In practice this deformation will not influence the profiling process as it will quickly wear off when profiling non-straight profiles. The wear behavior is dominated by the properties of the CVD diamonds resulting in a high G_d ratio of over 400.

![Figure 8-6: Arranged CVD diamond roll, detail of wear area](image)

From the non-diamond materials the hardened steel roll has a remarkably high G-ratio which can be explained by a good resistance against abrasive wear as well as fatigue wear while being hard enough to undergo little plastic deformation. When considering that regrinding the hardened steel form roll is very simple and quick the hardened steel roll might be usable if a means is provided for regrinding the form roll efficiently. A fully automated regrinding operation is necessary as the regrinding frequency will be high. The arranged CVD diamond form roll performs significantly better than the other materials and is therefore preferred. However regrinding will be much harder than for the hardened steel roll, therefore the grindability of this type of roll should be investigated, this is the subject of the next section.

### 8.3 Regrinding of form rolls

Regrinding of form rolls on the machines can be of benefit to the end-user. The fact that this is not implemented on existing machines is most likely because profiling units are often used for conventional grinding wheels, where the wear is low and regrinding intervals of the rolls can easily be several months. This does not ratify the investment in tools and equipment to regrind the rolls on the machine. For high accuracy diamond profiling the situation is different, in this case wear is high and the acceptable wear on the form roll small, motivating regrinding of the roll on the machine. In this section both the economic (8.3.1) and practical (8.3.2 and 8.3.3) feasibility of regrinding of the arranged diamond form rolls on the machine are studied.

#### 8.3.1 Economical considerations

The economy of the regrinding process is of primary importance for implementation in industry. Below the cost for the exchange of a worn form roll is calculated. Given these cost the maximum
time and cost spent on regrinding on the machine can be calculated. This will then be the target for the regrinding results presented in 8.3.3.

In the present situation form rolls are exchanged when worn and reground by an external company. The total cost of a form roll change when using external regrinding, \( K_{\text{ch,ex}} \), can be expressed as:

\[
K_{\text{ch,ex}} = \frac{K_{\text{roll}} + n_{\text{reg,ex}} \cdot ((K_{\text{op}} + K_{\text{mach}}) \cdot t_{\text{ch}} + K_{\text{reg,ex}}) + (K_{\text{op}} + K_{\text{mach}}) \cdot t_{\text{ch}}}{n_{\text{reg,ex}} + 1}
\]  

(8-1)

\( K_{\text{roll}} \) is the procurement cost of a roll in €, \( n_{\text{reg,ex}} \) the number of times the roll can be regrinded, \( K_{\text{op}} \) the cost of the operator and \( K_{\text{mach}} \) the cost of the machine both in €/hr. \( t_{\text{ch}} \) is the total time for changing the form roll including handling in hours. \( K_{\text{reg,ex}} \) is the cost of regrinding the form roll externally in €. The third term in the numerator represents the cost of mounting the form roll for the first time. According to the manufacturer regrinding of the form rolls is possible for \( n_{\text{reg,ex}} = 10\text{-}20 \) times, and the procurement cost of a new roll \( K_{\text{roll}} = € 2000 \). The regrinding cost is € 385, excluding shipping, for the type of roll used in this project [Hess07]. Exchanging the roll will also cost time, especially as this should be done carefully to achieve accurate mounting. Furthermore the tool should be prepared for sending it to the regrinder. Altogether 20 minutes for this procedure seems not exaggerated. Assuming the values shown in Table 8-2:

\begin{align*}
K_{\text{roll}} & \quad 2000 \text{ €} \\
K_{\text{op}} & \quad 75 \text{ €/hr} \\
K_{\text{reg,ex}} & \quad 385 \text{ €} \\
K_{\text{mach}} & \quad 100 \text{ €/hr} \\
K_{\text{ch,ex}} & \quad 0.33 \text{ hr} \\
n_{\text{reg,ex}} & \quad 10\text{-}20 \\
t_{\text{ch}} & \quad 0.33 \text{ hr} \\
K_{\text{reg,ex}} & \quad 385 \text{ €}
\end{align*}

Table 8-2: Assumed values for external regrinding of form rolls

and inserting these values in Equation 8-1 gives for the cost per change of roll:

\( K_{\text{ch}} (n_{\text{reg,ex}}=20) = € 520 \quad \text{and} \quad K_{\text{ch}} (n_{\text{reg,ex}}=10) = € 590. \)

When the form roll is regrinded on the machine the cost per change can be expressed as:

\[
K_{\text{ch,in}} = \frac{K_{\text{roll}} + n_{\text{reg,in}} \cdot (K_{\text{grind}} + (K_{\text{op}} + K_{\text{mach}}) \cdot t_{\text{reg,in}}) + (K_{\text{op}} + K_{\text{mach}}) \cdot t_{\text{ch}}}{n_{\text{reg,in}} + 1}
\]  

(8-2)

In which the subscript “in” is used for on the machine regrinding. \( K_{\text{grind}} \) represents the cost of the grinding wheel consumed in regrinding. As there is no information available on regrinding the form roll a starting point would be to determine, based on Equation 8-2, the amount of time that can be spent on regrinding, \( t_{\text{reg,in}} \) for a given cost of the form roll \( K_{\text{roll}} \). Assuming \( n_{\text{reg,in}} = n_{\text{reg,ex}} = 20 \) and therefore \( K_{\text{roll}} = € 520 \), the values given in Table 8-2 and assuming \( K_{\text{grind}} = € 50 \), it is found that \( t_{\text{reg,in}} = 2 \text{ hr 14 min}. \) This time is the target for regrinding of the form rolls to make internal regrinding economically viable.
The extra benefit of increased running accuracy, flexibility and autonomy are not considered here. If the regrinding process is automated the cost of the operator can be eliminated from Equation 8-2 reducing cost further. Also \( n_{reg,in} \) can be larger as the material removed can be less because of the lack of mounting errors. Another possible benefit is that less investment in form rolls is needed because a single roll, and possibly one roll at spare, is sufficient. In the case of external regrinding the minimum needed amount of rolls is determined by quotient of the time it takes getting a worn roll back and the time a roll can be used on the machine.

In the following sections it is verified that \( K_{\text{grind}} \leq \€ 50 \) and that \( t_{reg,in} \leq 2 \text{ hr 14 min} \) to make regrinding on the machine economically viable.

### 8.3.2 Form roll regrinding process

The kinematics to grind a radius on a diamond form roll were shown in chapter 6 and repeated in Figure 8-7a. The oscillating motion of the grinding wheel and the swiveling of the form roll should be independent. In this way the wear of the grinding wheel is averaged out over its width, maintaining a straight, flat grinding wheel. The shape of the radius on the form roll is determined by the motion of the form roll (swiveling around its center), therefore this process can generate an accurate radius on the form roll even with high wear on the grinding wheel. The grinding wheel is moved incrementally towards the form roll. In Figure 8-7b the influence of a wear flat on the form roll on the regrinding process is shown. When the form roll swivels contact with the grinding wheel is lost. By keeping the oscillating frequency of the grinding wheel considerably faster (ratio 1:5 or higher, depending also on grinding wheel width) than the swiveling frequency of the form roll the wear will be averaged over the grinding wheel width.

When the wear profile is known it can be advantageous to adopt a different strategy when grinding the form rolls, to maximize contact time and thereby increase the efficiency of the process.

*Figure 8-7: a) Form roll radius grinding process, b) influence of radius wear, c) material to be removed to create new top radius*
For example for the flat wear profile shown in Figure 8-7b the material to be removed during regrinding, after adjusting the form roll radially by $\delta_y$, is indicated in Figure 8-7c. The thickest layer of material to be removed is found at $\alpha_1 = \pm 45^\circ$. Furthermore at the flanks it can be seen that the contact width during regrinding will become large. It makes therefore sense to fix axis A in some positions and first grind facets and the flanks to approximate the shape of the radius. Finally swiveling can be started to create the full radius with the required accuracy.

Traditionally regrinding of form rolls is done on manual machines where the oscillating motion is executed by the machine, but the swivel axis is operated by hand. In this way the operator can automatically concentrate the grinding on the areas where material has to be removed. Contact between grinding wheel can simply be heard. Also the radial feed of the grinding wheel is affected by hand based on the sound of the contact.

To automate this process the “intelligence” from the operator should be integrated into the machine. For example acoustic emission sensors can be used to detect contact between grinding wheel and form roll. It has not been the goal of this work to realize fully automated form roll regrinding. For the research the form rolls are reground on the machine but with manually controlled radial feed of the grinding wheel and manual measuring of the resulting radius.

As there is no information readily available on grinding of diamond form rolls these values had to be found experimentally. However a full optimization of this grinding process has not been possible within the frame of this project. Below the used parameters and a qualitative discussion of the regrinding process are given.

**Regrinding tool**

Due to the hardness of the diamond rolls, grinding can only be done efficiently with diamond. As the bond type of the regrinding wheel used will have a strong influence on the process it has to be selected carefully. The bond should facilitate a high grinding pressure to enable material removal, however the regrinding forces should also be kept at an acceptable level. Resin bonded grinding wheels are unable to fulfill these requirements as they will deform in the contact zone, leading to a larger contact area and therefore low pressures and/or high forces. Metal bonded and vitrified wheels both show the preferred behavior as they have a much higher contact stiffness leading to higher contact pressures for a given normal force. As there will be little chip formation during the regrinding process, the chips will not aid the self sharpening of the process so vitrified grinding wheels are preferable because of their open structure, which makes them self-sharpening. Although metal bonded wheels have the advantage of a very high resistance against grain pull-out, grain dulling and lack of chip-space might become an issue. Furthermore, vitrified wheels will facilitate grinding fluid to enter the contact zone, avoiding thermal damage of the diamonds.
As the process was developed to be automated a porous vitrified grinding wheel was chosen as it was anticipated that with this type of wheel the wear will be higher, leading to quicker renewal of, and therefore sharper, cutting edges, resulting in a more constant process. This will be at the cost of increased wear leading to higher regrinding cost. Use has been made of a large porous vitrified diamond grinding wheel of which the specifications are shown in Table 8-3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>SD180 – K4V5 – 1/8</td>
</tr>
<tr>
<td>$d_s$</td>
<td>350 mm</td>
</tr>
<tr>
<td>Bond type</td>
<td>Vitrified</td>
</tr>
<tr>
<td>$b_s$</td>
<td>10 mm</td>
</tr>
<tr>
<td>Concentration</td>
<td>100 (25% Vol.)</td>
</tr>
<tr>
<td>Diamond layer thickness</td>
<td>3 mm</td>
</tr>
<tr>
<td>Porosity</td>
<td>22.5 % Vol.</td>
</tr>
<tr>
<td>Price</td>
<td>€ 875</td>
</tr>
<tr>
<td>Average grain size</td>
<td>85 µm</td>
</tr>
</tbody>
</table>

Table 8-3: Specification of a grinding wheel for regrinding of the form roll

The experimental results support the motivation given above. During grinding the process did not show a build up of forces that would indicate dulling of the grains due to too high grain holding forces. The wear on the grinding wheel was, as expected, considerable. A more extended experimental verification of various bond types might result in a more balanced set of properties of the regrinding process. In further research the use of a harder vitrified bond can be investigated as it might give better performance without sacrificing the constant process behavior. Metal bonded wheels could be investigated too, as the high grain holding forces might lead to lower wear of the grinding wheel, combined with a lower purchase price this can lead to reduced cost.

### Re-grinding parameters

During re-grinding the parameters given in Table 8-4 have formed the basis of the process.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{re}$</td>
<td>Radial feed grinding wheel in regrinding</td>
</tr>
<tr>
<td>$v_{re}$</td>
<td>1 µm/swivel up to 1 µm/oscillation</td>
</tr>
<tr>
<td>$v_{s,re}$</td>
<td>Grinding speed in regrinding</td>
</tr>
<tr>
<td>$v_{osc}$</td>
<td>30 m/s</td>
</tr>
<tr>
<td>$q_{r,re}$</td>
<td>Speed ratio in regrinding</td>
</tr>
<tr>
<td>$v_{swiv}$</td>
<td>Swivel speed in regrinding</td>
</tr>
<tr>
<td>$v_{osc}$</td>
<td>200 °/min (1.66 osc./min)</td>
</tr>
<tr>
<td>$v_{swiv}$</td>
<td>170 mm/min (8.5 osc./min)</td>
</tr>
</tbody>
</table>

Table 8-4: Form roll regrinding parameters

The acoustic emission signal was used to detect contact with the form roll. This gives the operator an indication if and where along the radius there is contact. Based on the magnitude of the AE signal the feed $a_{re}$ was adapted. The feed was given manually in increments of 1 µm. When the full radius is in contact $a_{re} = 1$ µm per oscillation of the grinding wheel proved effective. Too small values of $a_{re}$ resulted in inefficient material removal. There seems to exist a threshold value for
the contact pressure in grinding; if the contact pressure is below this limit there is virtually no material removal on the form roll, in this way the grinding wheel and time are wasted.

Although it is possible to grind a radius by swiveling from the first moment over the full range (+60° to -60°) it proved worthwhile to machine the flanks first. The main problem on the flanks is that the contact area is considerably larger than on the rest of the profile. Even if the material removal rate is the same at this point the radial removal will be less due to the larger amount of material that has to be removed there. This was seen during regrinding: a radius would be formed but the flanks remained at an elevated level. Grinding the flanks separately down to a few µm above the desired level made the whole regrinding operation better controllable, the resulting radius more accurate and reduced the total regrinding time. When regrinding the flanks it was noticed that a small swivel motion, e.g. from 55-60 degrees, was beneficial. This was done to reduce the contact area, compared to the situation in which the form roll would be kept stationary in the extreme 60 degree position.

8.3.3 Regrinding performance

In the experiments the wear of the form roll has been limited to 20 µm radial wear. Regrinding of the form roll took about 30-40 minutes grinding time. Added to this should be the adjustment and measuring time which is around 30-60 minutes. The total time is therefore \( T_{\text{reg,in}} = 1 \text{ hr 40 min} \) which is below the limit of 2 hr 14 min mentioned in 8.3.1. For the wear limit of 20 µm about 150-200 µm of the selected grinding wheel was consumed. Given the cost from the wheel this leads to a \( K_{\text{grind}} \) of € 41-55. Which is acceptably close to the value of \( K_{\text{grind}} = € 50 \) assumed in 8.3.1.

The geometrical quality of the ground radii was verified both with a measuring microscope and a profilometer and showed a profile accuracy of 2 µm which is comparable to the profile accuracy of a newly manufactured roll. Figure 8-8 shows an imprint in graphite of a reground form roll with a radius of \( R_{\text{top}} = 110 \mu m \).

Achieving the form accuracy proved to be less difficult than achieving a predefined radius. This is due to the fact that the material removal is not very predictable. Experience and integrated measuring will be of help when defined radii are needed. However the radius can easily be compensated in the machine tool control and this is readily implemented on NC grinding machines. Grinding a radius to an accuracy of +/- 5 µm showed to be achievable without much measuring effort, and is sufficient for most applications.
8.3.4 Conclusion regrinding form rolls

Regrinding of the form roll on the machine proved to be practically and economically feasible with the developed set-up and a vitrified diamond grinding wheel. The results mentioned have to be regarded as a starting position. Optimization regarding 1) the choice of the grinding wheel, 2) the process parameters and 3) the measuring procedure are possible. It is expected that further investigation can improve the mentioned regrinding times as well as the grinding wheel consumption considerably, leading to an even more efficient process.

8.4 Calculation of form roll wear

Knowledge of the exact diameter of form rolls as well as grinding wheels is for most grinding processes not strictly necessary. Therefore these dimensions are measured with a caliper when the tools are mounted on the machine and these values are entered into the machine control. When a profiling operation is performed the machine control is not taking into account the wear of the profiling tool and alters the actual grinding wheel diameter \( d_w \) by \( 2a_m \) after profiling. For conventional grinding wheels the error made is small and once in a while the operator can adjust the diameter of the form roll and grinding wheel when the deviation becomes too large. For profiling of super-abrasive grinding wheels the diameter of the form roll varies much faster and therefore the prediction of the diameter of the grinding wheel is less accurate. This will result in increased depth of cut in grinding, \( a_n \), leading to out-of-tolerance parts. It is common in industry to correct for this effect by measuring the dimensions (thickness) of the workpieces and compensate for the deviation when it becomes too large.
Determining the wear (or diameter) of the form roll in a straightforward and reliable way on the machine is therefore attractive for the end-user, especially when processes have to be automated. In the designed set-up information on the angular speed of the form roll, \( \omega_{rd} \), is available. When the grinding wheel and the form roll have the same circumferential speed, \( v_{rd} = v_{sd} \) and the angular speed of the grinding wheel, \( \omega_{sd} \), and the depth of cut in crushing, \( a_{ed} \), are known, the diameter reduction of form roll and grinding wheel can theoretically be determined.

Assuming the angular velocity of the grinding wheel, \( \omega_{sd} \) is constant, the average angular velocity of the form roll, \( \omega_{rd} \), in a given crushing pass \( k \), in dependence of the radial wear per pass, \( \delta_r \), and the crushing depth, \( a_{ed} \), is given by:

\[
\omega_{rd}(k + 1) = 1 - \left[ \frac{(2 \cdot a_{ed} - 2 \cdot \delta_r)}{d_{s,0} - (2 \cdot a_{ed} - 2 \cdot \delta_r) \cdot k} \right] \left[ \frac{d_{r,0} - k \cdot 2 \cdot \delta_r}{d_{r,0} - (k + 1) \cdot 2 \cdot \delta_r} \right] \cdot \omega_{rd}(k) \tag{8-3}
\]

In which \( d_{r,0} \) and \( d_{s,0} \) are the initial diameters of the form roll and grinding wheel, respectively. The first quotient determines the change in \( \omega_{rd} \) caused by the change in diameter of the grinding wheel. The second quotient accounts for the change of \( \omega_{rd} \) due to the change in diameter of the form roll. In the rest of this discussion it is assumed that the radial wear per profiling pass is constant. Based on the work of Hessel [Hess03] this is an acceptable approximation for the wear range of interest.

This expression can be simplified when it is considered that:

\[
\begin{cases}
k \cdot (2 \cdot a_{ed} - 2 \cdot \delta_r) \ll d_{s,0} \\
d_{r,0} - k \cdot 2 \cdot \delta_r \\
d_{r,0} - (k + 1) \cdot 2 \cdot \delta_r = 1
\end{cases}
\tag{8-4}
\]

Reducing Equation 8-3 to:

\[
\omega_{rd}(k + 1) = \left[ 1 - \frac{2 \cdot (a_{ed} - \delta_r)}{d_{s,0}} \right] \cdot \omega_{rd}(k) \tag{8-5}
\]

Simplifying this notation by defining:

\[
A = \left[ 1 - \frac{2 \cdot (a_{ed} - \delta_r)}{d_{s,0}} \right]
\tag{8-6}
\]

Reduces Equation 8-5 to:

\[
\omega_{rd}(k + 1) = A \cdot \omega_{rd}(k) \tag{8-7}
\]

Which can be expressed in the following form:

\[
\omega_{rd}(k) = \omega_{rd,0} \cdot A^k \tag{8-8}
\]

From the measurements of the angular speed of the form roll, the average within every dressing pass can be calculated and based on these values, \( A \), and therefore wear, can be calculated.
Averaging of the speed measurements over (part of) the grinding wheel contour reduces the influence of noise and process variance on the wear estimate.

When Equation 8-8 is expressed as:

$$\ln \omega_{rd}(k) = \ln(\omega_{rd,0} \cdot A^k) = \ln \omega_{rd,0} + k \cdot (\ln A)$$  \hspace{1cm} (8-9)

the data can be fitted in a linear way, to find $\ln A$. From this $\delta_0$ is found and the accumulated wear is found by:

$$\delta_{r,tot} = k \cdot \delta_r$$  \hspace{1cm} (8-10)

In Figure 8-9b the average speed per pass of a set of 50 profiling passes is shown. Clearly the angular speed of the form roll $\omega_{rd}$ decreases with every pass. However due to the fact that the grinding wheel speed is assumed constant, but not measured an error might be introduced. Within one set of profiling passes the grinding wheel angular speed seemed to be constant, however as shown in Figure 8-9a the speed of the grinding wheel is not constant over all sets of profiling passes, in which case Figure 8-9a should be monotonously decreasing.

After a set of passes the machine tool recalculates the diameter of the grinding wheel (assuming no wear) and this value is used in the next set of passes to calculate the angular velocity of the grinding wheel based on the predefined circumferential speed $v_{sd}$. However the starting speeds in every set do not show a clear trend, indicating that the main spindle control is not very accurate.

The data of Figure 8-9 were analyzed per set and the results added, resulting in a total radial wear of 29 µm, while 27 µm was measured during the experiments. However as this method can only be used within a set of profiling passes and the accuracy becomes better as the number of passes becomes larger, this method has limited application.

Measurement of the grinding wheel angular speed would enhance the accuracy of the estimate of the form roll wear as it would enable to account for the variations in grinding wheel angular speed.
both within and between sets of profiling passes. In this way all data from the moment a form roll and grinding wheel set is put into use can be used to estimate wear, increasing the relative accuracy of the estimate.

The ratio of the average angular speeds $\omega_{rd}$ and $\omega_{sd}$ in a profiling pass $k$ can be expressed as:

\[
\frac{\omega_{rd}}{\omega_{sd}} = \frac{D_{s,0} - (2 \cdot a_{sd} - 2 \cdot \delta_{tot}) \cdot k}{D_{r,0} - 2 \cdot \delta_{tot} \cdot k} \cdot \frac{\omega_{sd,0}}{\omega_{sd,0}}
\]  

(8-11)

Which can be solved for the wear $\delta_{r,tot}$:

\[
\delta_{r,tot} = D_{r,0} \cdot \frac{\omega_{rd}}{\omega_{sd}} - D_{s,0} \cdot \frac{\omega_{sd,0}}{\omega_{sd,0}} + 2 \cdot k \cdot a_{sd} \cdot \frac{\omega_{sd,0}}{\omega_{sd,0}} \cdot \frac{D_{k} \cdot (2 \cdot \delta_{tot})}{D_{k} \cdot (k + 1) \cdot 2 \cdot \delta_{r}}
\]

(8-12)

In this expression no assumption on the relation between radial wear and the amount of profiling passes is made. However in this way only the speed ratio of one profiling pass is used.

A recursive formulation as in Equation 1.11 can be advantageous as in this way the speed ratios of all profiling passes are used, increasing the accuracy of the estimate. However a constant radial wear per profiling pass has to be assumed. This would lead to the following expression:

\[
\frac{\omega_{rd,0}}{\omega_{sd,0}} (k + 1) = \frac{D_{s,0} - (k + 1) \cdot (2 \cdot a_{sd} - 2 \cdot \delta_{r})}{D_{r,0} - (k + 1) \cdot 2 \cdot \delta_{r}} \cdot \frac{\omega_{sd,0}}{\omega_{sd}} (k)
\]

(8-13)

which can be treated in a similar way as described for Equation 8-3.

The above mentioned method opens up the possibility to calculate the grinding wheel and form roll radii in-process. This is a step towards fully automated, high accuracy grinding. The data needed will be available in most NC grinding machines, therefore the additional investment will be limited. As this method uses in-process available data, this method does not cost additional time like time required to measure the grinding wheel diameter with AE or time to measure on the machine the workpiece dimensions with touch probes.

8.5 Summary and conclusion

In this chapter it was shown that it is possible to use several materials for the form roll in crushing. Dedicated form crushing rolls with CVD diamond bars outperformed all other materials by far. Of the other materials hardened steel gave the best results. Regrinding of the diamond crush roll was done on the grinding machine and proved to be technically possible as well as economically viable. Also a method was developed enabling the in-process determination of the grinding wheel and form
roll diameters and thereby radial wear of the form roll, showing perspective towards increased accuracy in automated grinding.
9 Process optimization

In this chapter the influence of process parameters with respect to profiling time, profile accuracy and achievable profile feature size is described. These issues are treated together because of their interrelation. Therefore this interrelation is first discussed in sections 9.1.1 and 9.1.2. A comparison between form dressing and form crushing is made in 9.2, to compare the damages to the grinding wheel created by both methods. In section 9.3 the influence of the grinding wheel properties on the crushing and grinding results are studied. This is followed by a study into the influence of the crushing depth (9.4) and the contact width during crushing (9.5).

9.1 Profiling performance

Important parameters to evaluate the performance of a profiling process are the time it takes to create a profile: the profiling time, and the accuracy of the profile and the achievable profile features. In the following two sections the process parameters influencing these profiling performance parameters are discussed.

9.1.1 Profiling time

One of the main drawbacks of form profiling is the relatively long profiling time. Primarily this is due to the fact that only a small area of the grinding wheel is in contact; this is inherent to every form profiling process. Given this fact the profiling times could be reduced by decreasing the \( U_d \) ratios, increasing the profiling speed \( v_{sd} \) and increasing the depth of the crushed layer in a single pass, \( a_{cr} \).

Earlier work by Hessel [Hess03] has shown that increasing the \( U_d \) ratio has little effect on the process. It lowers the forces in crushing a little, reduces the wear ratio and has a very small influence on the grinding wheel topography. On profiled grinding wheels little to no influence was observed. Therefore a small \( U_d \) value is chosen in this chapter to minimize process time. Values of 2-4 seem reasonable based on Hessel’s work. In this chapter a value of \( U_d = 2 \), based on a form roll without wear is used.

The second possibility to reduce profiling time is by increasing of the cutting speed in crushing, \( v_{sd} \). The work of Hessel has shown that form roll wear and crushing forces decrease with increasing crushing speed. No effect was noted on the grinding wheel topography. However when the effect was tested on profiles the speed showed a negative influence; higher speeds led to increased wear of the profile. Hessel related this higher wear to “dynamic effects”. The measured lower forces
could be related to the process but could also be due to the fact that at the higher speed, the measured forces will contain a larger amount of higher frequency components. At higher speeds there will be higher frequency components that are filtered out, resulting in an (incorrect) lower reading of the force. As the author specifies no information on the low pass filtering used this cannot be excluded. However the lower forces could explain the lower form roll wear.

Another argument to profile grinding wheels at higher speeds is that principally, profiling should be done at the same speed as grinding; \( v_{sd} = v_s \). In this way the dynamic response of the machine is the same in both processes, leading to higher running accuracy of the profiled wheel. The standard speed \( (v_{sd} = 10 \, \text{m/s}) \) used in the research by Hessel is below the normally used range for vitrified diamond grinding wheels \( (v_s = 20-40 \, \text{m/s}) \). This further motivates the use of higher speeds.

In this chapter profiling is performed at the same speed as the grinding speed, \( v_{sd} = v_s = 25 \, \text{m/s} \).

A third parameter to influence the profiling time is the crushing depth. The higher this value, the higher the initial wear of the profile was shown by Hessel. Also crushing forces increased with higher crushing depth, as expected. In Hessel’s work little to no influence of the crushing depth on the wear of the form roll was noticed.

This shows that there will be a balance: reduction of profiling time is balanced by the demand for accurate profiling. In section 9.4 the influence of the crushing depth will therefore be investigated experimentally and quantified.

9.1.2 Profile accuracy and profile feature size

Profiling accuracy can be defined as the difference between the demanded profile and the realized profile in the workpiece. Profile feature size deals with the smallest details that can be realized in a profiled wheel.

Both parameters are influenced by two effects:

- Wear of the form roll
- The material removal mechanism

Wear of the form roll leads to an error in the tool path that generates the profile, affecting profile accuracy. Also when the wear is relatively fast it might make the use of small form roll top radii unpractical, limiting the usable roll top radii and therefore the achievable profile detail.

The wear of the form roll will, for a given grinding wheel, be influenced by the process parameters \( (a_{sd}, U_d, v_{sd}) \). Beside these process parameters the choice of the grinding wheel composition will influence the wear of the form roll.

The material removal mechanism (crushing) will lead to certain damage to the outer layer of the grinding wheel surface. This damage gives rise to increased wear at the beginning of the grinding process. This so-called initial wear reduces the achievable profile accuracy and feature size. The
damage of the profiling operation can, for a given grinding wheel, be influence by the profiling parameters \( (a_{ed}, u_d, v_{sd}) \). It seems for example likely that a reduced depth of cut in profiling will lead to less damage of the grinding wheel. The grinding wheel composition will also influence the damage to the wheel during crushing. This is likely as for example the brittleness of the binder can be influenced with the binder composition and the porosity.

Because of the argument given above both the initial wear (= damage to grinding wheel structure) and the wear of the form roll are important parameters, influencing the profile accuracy and feature size.

The discussion given in the two preceding sections has led to the formulation a set of different experiments of which the results are discussed in the following sections. In section 9.2 form crush dressing and rotary diamond dressing are compared, damage to the grinding wheel due to the dressing operation is given extra attention. Section 9.3 introduces crushing and grinding results for different grinding wheel compositions. Section 9.4 discusses the influence of the crushing depth, \( a_{ed} \). In section 9.5 the influence of the contact width in dressing, \( b_d \), is discussed.

### 9.2 A comparison of form crushing and rotary diamond dressing

To compare form crushing and rotary diamond dressing an experiment was defined using the two methods in exactly the same situation [Derk05]. The experiments consisted of profiling a straight profile on a vitrified D46 grinding wheel with three different speed ratios: \( q_d = -0.7, 0.7 \) and 1. This was done on a tool grinder equipped with an industry standard frequency controlled dressing spindle fitted with a diamond form roll. The used parameters are summarized in Table 9-1.

<table>
<thead>
<tr>
<th>Dressing</th>
<th>Grinding</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b_d )</td>
<td>1 mm</td>
</tr>
<tr>
<td>( U_d )</td>
<td>4</td>
</tr>
<tr>
<td>( q_d )</td>
<td>-0.7 / 0.7 / 1</td>
</tr>
<tr>
<td>( v_{sd} )</td>
<td>18 m/s</td>
</tr>
<tr>
<td>Form roll</td>
<td>Metal bonded natural diamond D1001</td>
</tr>
<tr>
<td>( d_f )</td>
<td>120 mm</td>
</tr>
</tbody>
</table>
| \( a_{ed} \)   |\begin{align*}1 \mu m \ (q_d= 1) \\
            3 \mu m \ (q_d \neq 1)\end{align*} |
| \( a_{ed,tot} \)| 15 \mu m                  |
| \( v_{fr} \)   | 79 mm/min                 |
| \( v_s \)      | 18 m/s                    |
| \( d_s \)      | 70 mm (D4-8 100 mm)       |
| L_s            | 400 mm                    |
| Q_w            | 4.4 mm³/min/s             |
| Material       | WC-10%Co 0.5-0.8 \mu m grain size |
| Coolant        | Synthetic, water soluble 4% conc. |

Table 9-1: Experimental settings comparison rotary form dressing and -crushing

All three settings were tested and the dressing result was tested in a subsequent grinding operation. This grinding operation was very intensive to visualise the damage of the grinding layer
by the initial wear; damage to the structure will lead to breakout of the involved grains. In Figure 9-1, right the wear results of the grinding wheel are shown. The wear curves can be described by two parameters: an initial wear amount ($\Delta r$, in $\mu$m radius reduction), visible after grinding only about 10 mm and a steady state wear rate (expressed by the G-ratio). It can clearly be seen that changing from $q_d = 0.7$ to $q_d = 1$ does not affect the initial wear. Therefore initial wear is not a problem solely related to crushing. As can be seen from the results for $q_d = -0.7$ initial wear is much less in this case, but still present. The slope of the three wear curves is similar, indicating that the initial wear is influenced by the dressing method (speed ratio $q_d$) but the wear rate is not.

This can be explained as the wear rate is basically determined by the grinding wheel properties and the grinding parameters which were not varied in this test. Other authors have also reported initial wear after dressing, also with different dressing methods, e.g. Spur [Spur87] reported increased wear after block sharpening.

Apart from grinding wheel wear, cutting forces and dressing forces were measured. The specific normal grinding forces are shown in Figure 9-1, left. Because of the intense grinding parameters grinding forces rise due to wheel loading. The forces show the same trend as the wheel wear: there is little difference between $q_d = 1$ and $q_d = 0.7$, $q_d = -0.7$ leads to significantly higher forces which is expected because this speed ratio creates a smoother and less aggressive wheel surface leading to increased cutting forces. This is also confirmed by the roughness results shown in Figure 9-2, the smoother surface of the wheel dressed with $q_d = -0.7$ results in the lowest workpiece roughness. The only significant difference between the $q_d$ values 1 and 0.7 is seen in the dressing forces, Table 9-2. The normal forces in crushing are almost 4 times higher. This difference is even more striking when considering that the depth of cut in crushing was 1 $\mu$m and in rotary diamond dressing 3 $\mu$m.
It can be concluded that initial wear is present in both dressing situations and that the generally used value for profiling of diamond wheels of $q_d = 0.7$ leads to comparable grinding results as form crushing ($q_d = 1$). The negative speed ratio of $q_d = -0.7$ shows different results but is not often used in practice as wear of the dress tool and grinding forces increase significantly. The accuracy that can be achieved with these dressing methods is therefore strongly dependent on the initial wear of the grinding wheel and the wear of the form roll.

### 9.3 Influence of grinding wheel properties on crushability and grinding

The properties of the grinding wheel are the key factor to its crushability. Only bond systems that behave brittle can be used for crushing. Within the range of brittle bond systems there is a vast range of parameters to adapt the grinding wheel properties to the grinding and profiling task. These parameters include: type, average size and concentration of the diamond particles, type of binder, amount and type of porosity and hardness and were introduced in chapter 2.

To quantify the influence of each property, including the interdependent relationship between parameters requires a vast experimental investigation, which was outside the scope of this project. Instead the viability of crush-profiling is examined by the selection of six typical wheel specifications with high potential in crush profiling. These wheels have been selected in consideration with specialists from various grinding wheel manufacturers. The results will indicate to what extent the profiling and the grinding process can be influenced by the grinding wheel
specifications and how the various, and seemingly contradictory demands of these processes influence each other.

9.3.1 Grinding wheel properties

Bond system

The properties of the grinding wheels selected for these tests are shown in Table 9-3. As can be seen 5 out of the 6 wheels have a vitrified bond system. This bond system is attractive because of its self-sharpening properties and its brittleness.

<table>
<thead>
<tr>
<th>Wheel name</th>
<th>Wheel designation</th>
<th>Concentration</th>
<th>Bond system</th>
<th>Work hardness</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>D46-V+2046-L-S</td>
<td>C150</td>
<td>Vitrified</td>
<td>L (hard)</td>
<td>Low, no pores added</td>
<td></td>
</tr>
<tr>
<td>D46-V+2646-J-S-C100-23</td>
<td>C100</td>
<td>Vitrified</td>
<td>J (medium)</td>
<td>Medium, added pores</td>
<td></td>
</tr>
<tr>
<td>D46-DMC-C75-23</td>
<td>C75</td>
<td>Bronze / Tin</td>
<td>Medium / hard</td>
<td>Graphite pores</td>
<td></td>
</tr>
<tr>
<td>D46-D10U-J-S-C150</td>
<td>C150</td>
<td>Vitrified</td>
<td>J (soft)</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>D46-NV3466-S-23</td>
<td>C50</td>
<td>Hot-pressed vitrified</td>
<td>Very hard</td>
<td>No pores</td>
<td></td>
</tr>
<tr>
<td>D4/8-MIC-K2V5-K-V-C50</td>
<td>C50</td>
<td>Vitrified</td>
<td>K (medium)</td>
<td>Medium 22.5 %</td>
<td></td>
</tr>
</tbody>
</table>

Table 9-3: Properties of grinding wheels included in comparative experiment

Also a special class of vitrified bonds is included, called hot-pressed vitrified. These grinding wheels have a bond that is very brittle of itself but the wheels have no added porosity, resulting in a brittle grinding wheel with a dense structure resulting in a high hardness.

One wheel with a crushable metal bond (DMC) is included to investigate its crushability and grinding properties. The high grain retention forces of the metal bond might be advantageous for the profile wear. The first grinding wheels used for profile crushing used this bond system, at that time the vitrified bond was not yet available for diamond grinding wheels. The bond consists of copper and tin in a ratio of 3:2, furthermore graphite particles are added to create porosity [Geis80]. Form crushing has not yet been tested on bronze bond diamond wheels.

Grain type

The type of grain used in the grinding wheel can be very different: man-made (synthetic) or natural, blocky or sharp, friable or tough, etc. As far as possible the grinding wheels used from one manufacturer were specified with the same type of diamond to exclude this influence. Therefore all
grinding wheels bearing “23” at the end of the wheel designation have the same diamond type. This synthetic diamond abrasive has irregular shapes and medium friability. The D4/8 wheel contained (a different type of) synthetic diamonds. The diamond used in the D10U wheel was not specified by the manufacturer.

**Concentration**

The concentration of the grinding wheels indicates the volume percentage of diamond used. A standard concentration for normal grain sizes (D46-D128) would be C100 (25 % Vol.). In the experiments wheels ranging from C50 (12.5 %Vol.) to C150 (= 37.5 % Vol.) are used. At very small grain sizes lower concentrations are common as explained in chapter 2; therefore the ultra fine grained grinding wheel (D4-8) had a lower concentration of C50.

**Grain size**

A normal range of grain sizes ranges from D46 to D128. Because the underlying work focuses on accurate profiles with intricate details and the crushing process removes complete grains, the use of smaller grain sizes is preferred. Another consideration is that the grinding wheel structure after profiling is rather coarse, compared to e.g. SiC dressing. Therefore smaller grains are necessary to achieve the demanded surface roughness. On the other hand the achieved surface topography results in a rather aggressive cutting surface, enabling efficient use of smaller grain sizes.

The foregoing arguments have led to the choice of D46 as the standard grain size for the experiments. This grain dimension balances good grinding capacity, small profile detail and acceptable surface roughness. To study the influence of very small grain sizes a wheel with D4-8 grain size is also included.

**Grinding hardness**

The resistance of a grain to being pulled out of the bond is called the grinding hardness. Harder wheels will be more difficult to profile as the force to break the grain out of the binder will be higher. The tested wheels have different hardness, in Table 9-3 a relative comparison is given, based on the information provided by the manufacturer. No absolute values were available.

**Porosity**

The spaces in the grinding wheel, not occupied by grains or binder, are called pores. These pores enable cooling fluid to better reach the grinding zone and create chip space, giving these wheels their self-sharpening properties.

For crushing the pores serve another goal: they make it possible to dislocate one grain and limit the crack formation into the rest of the grinding wheel. In this way the damage to the grinding
layer is reduced and the material removal localized. Little information on the amounts of porosity was available, in Table 9-3 the information is presented.

**Selected wheels**

The 6 wheels shown in Table 9-3 are not sufficient to isolate the influence of all the above mentioned parameters. The goal of this investigation is to see how wide the range of crushable wheels is and what are the trade-offs and limitations. The motivation for the choice of wheels is given below: The wheel designated by D10U was specially developed for form crushing and should be comparable (though not exactly the same) to the wheels used in the research on form crushing by Denkena [Denk04].

The V+2646 is a vitrified grinding wheel that is commonly used for profile grinding and is regularly employed in form dressing and therefore a logical choice to test as the demands on the wheel for this application are comparable.

To explore the limits of the process a wheel with the same bond system and diamond type and size, but with 50 percent higher concentration, higher hardness and lower porosity was included. The properties are still in a usable range for carbide grinding.

A brittle bronze bonded wheel designated by DMC (Diamond Metal Crushable) was included to investigate the performance of a metal bonded crushable wheel. The same diamond type is used as for the other wheels specified with “23” at the end. The concentration is chosen a little lower (C75) which is common for this type of bond. With higher concentrations the grinding hardness would be too high for the creep feed grinding application.

The special class of hot-pressed vitrified grinding wheels indicated by NV 3466 was included to verify if a very hard but brittle grinding wheel without added porosity is crushable. Its concentration is kept low at C50 to reduce its grinding hardness.

### 9.3.2 Test set-up and procedure

All the mentioned grinding wheels were used for crushing and subsequent grinding to compare their relative performance. Every experiment was started with an unworn crushing roll with a top radius of 110 µm (+/- 5 µm). The grinding wheels were mounted and trued with the non-driven crushing tool (see chapter 5) until run-out was removed. This was monitored by the AE signal and checked with a mechanical gauge with 2 µm resolution. In the next step profiling of a straight profile was started and continued till the wear limit of 30 µm radial wear of the form roll was reached. During profiling the crushing normal forces, form roll wear and grinding wheel diameter reduction were measured. After reaching the wear limit the grinding wheel was used to grind a tungsten carbide based hardmetal. During the grinding process the grinding wheel wear and
grinding forces were recorded. Furthermore the kinematic profile of the grinding wheel was 
imprinted in graphite and measured.

The parameters used in crushing and grinding are shown in Table 9-4 below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Form crushing</th>
<th>Grinding</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{ed}$</td>
<td>1 (2,4,6) µm</td>
<td>$a_e$ 1 mm</td>
</tr>
<tr>
<td>$U_{d, theo}$</td>
<td>2</td>
<td>$v_t$ 90 mm/min</td>
</tr>
<tr>
<td>$v_{fad}$</td>
<td>Approx. 100  mm/min</td>
<td>$v_s$ 25 m/s</td>
</tr>
<tr>
<td>$d_e$</td>
<td>120 mm</td>
<td>$d_e$ 70 mm</td>
</tr>
<tr>
<td>$R_{top}$</td>
<td>115 µm</td>
<td>$L_s$ 400 mm</td>
</tr>
<tr>
<td>Top angle</td>
<td>60º</td>
<td>Coolant 4%, synthetic, water soluble</td>
</tr>
<tr>
<td>Form disc</td>
<td>Set CVD diamond</td>
<td>Material WC-10%Co 0.5-0.8 µm grain size</td>
</tr>
</tbody>
</table>

Table 9-4: Crushing and grinding parameters for comparative grinding wheel experiment

A crushing depth of $a_{ed} = 1$ µm was used as this is advisable to be used in finish-profiling as will become clear in section 9.4. The overlap ratio is kept low at the minimum value of $U_d = 2$, which is acceptable as it is understood that when wear progresses the effective overlap ratio increases due to the increasing contact width $b_d$. Depending on the actual grinding wheel diameter and form roll top-radius the axial feed in dressing, $v_{fad}$ is calculated, values where around 100 mm/min for the wheels with $d_e = 75$ mm. The grinding wheel speed in dressing and grinding was kept equal as argued before. A grinding speed of $v_s = 25$ m/s was used, being a commonly used speed for this type of diamond wheels. The following grinding operation was performed in creep feed grinding mode with a feed of $v_f = 90$ mm/min at a depth of cut $a_e = 1$ mm, resulting in a machined volume per second per mm grinding wheel width $Q_w'$ of 1.5 mm³/mm·s.

In the four sections below the form roll wear, crushing forces, grinding forces and grinding wheel wear for the different grinding wheels are shown and discussed.

### 9.3.3 Form roll wear for different grinding wheel properties

The radial form roll wear is depicted in Figure 9-3. Shown in the upper graph is the radial wear in µm as a function of the removed volume of grinding wheel material $V_w$. From this figure it can be seen that, first of all, the ultra-fine grained D4-8 grinding wheel results in considerably lower wear of the form roll than in combination with the D46 grinding wheels. This can be partially explained by the low concentration of diamond in this wheel. Among the D46 wheels the V+2046 results in clearly higher form roll wear than the others. This can be explained by the 50% higher diamond
volume in combination with the higher hardness of the bond. In the lower graph of Figure 9-3 the result is presented in G_d ratios, the data of the D4-8 wheel is omitted for clarity.

![Figure 9-3: Form roll wear for different grinding wheels](image)

Even though at small V_s the measurement of the form roll wear is relatively inaccurate, it is clearly visible that the V+2046 creates a significantly lower G_d ratio of 265 than the V+2646 (G_d = 446), the D10U (G_d = 399) and the DMC (G_d = 391). The harder bond system of the DMC was expected to result in higher wear of the form roll. It seems however that this effect is compensated by the lower diamond concentration in this grinding wheel. The D4-8 wheel resulted in a G_d ratio of 5850. This value cannot be explained by the lower diamond concentration alone. Apparently the lower grain size has a significant influence on the low wear of the form roll. When these results are compared to the results published by Hessel [Hess03] it is seen that Hessel achieved higher G_d values compared to the D46 wheels. Part of this difference can be explained by the smaller grain size used in his work.
9.3.4 Crushing normal forces

During every crushing pass the normal forces were measured as described in chapter 6. In Figure 9-4 these forces are plotted. Shown is a filtered version of the force signal, for readability, the original data can be found in appendix B.

![Figure 9-4: Crushing normal forces for different grinding wheels](image)

It can be seen that the harder bond systems of both the DMC and the V+2046 wheels lead to considerably higher crushing forces. The D10U grinding wheel shows low and consistent force levels. The V+2646 wheel, on the contrary, shows large variations in the forces. These variations seem to become smaller when wear progresses on the form roll. The average force level does however not vary. It seems that there is a kind of process instability that leads to these varying forces. Possibly the material removal becomes larger with increasing forces. Effectively this would increase the amount of material removed per pass, thereby reducing the pretension of the system and reducing the forces again. Hessel also noticed such a behavior in his work [Hess03]. When the form roll wears the contact width increases, thereby averaging out this effect.

The D4-8 wheel has a force level slightly above the level of the V+2646 wheel. Even though the wear of the form roll was much smaller (resulting in a smaller contact width than the other wheels) the forces are not lower for this wheel. This implies that grain size has a much stronger effect on the crushing forces than binder hardness. Due to the smaller grain size the distance between the grains is smaller. The depth of cut in crushing was however for all wheels the same ($a_{cut} = 1 \, \mu m$). The depth of cut as a percentage of the grain size and spacing is for the D4-8 wheel 5 to 10 times higher, leading to increased forces.

The average crushing force levels of the grinding wheels can be recalculated to specific forces by division by the contact width ($b_c=155 \, \mu m$ at the radial wear limit of 30 $\mu m$), this leads to the results shown in Figure 9-5.
Other researchers have used grinding wheels comparable to the D10U wheel used in this research. In their work it was also shown that the specific crushing normal force increases with decreasing grain size. This was based on 4 different grit sizes ranging from D91 to D20-30. Their results show a specific crushing normal force of about 15 N/mm for a D54 grinding wheel, which is close to the D46 wheel used in this research [Denk04]. The results of Hessel [Hess03] show larger forces. However the used binder system is different, making comparison difficult.

For the complete system of the grinding and the crushing unit the measured forces are within an acceptable range. Taking the system stiffness into account, see chapter 6, the deformations caused by these forces are below 1 µm and will therefore not lead to significant deviations of the programmed profile.

9.3.5 Grinding forces

The normal forces as well as the tangential forces in grinding were measured and are shown in Figure 9-6. While the D10U and the DMC grinding wheels show forces that are relatively constant over the grinding length, the other 2 D46 wheels show increasing forces. This increase indicates that grains are flattening, resulting in increased grinding forces. The D10U and DMC wheels seem to self-sharpen effectively. This can either be due to grain pull out, or grain fracture. As the grinding length is limited no final statement can be made about the non-self-sharpening wheels. These wheels might reach the self-sharpening stage only later in the wear curve or forces might continue to rise until reaching an unacceptable level.

The high forces of the V+2046 are caused by the high concentration on the one hand and the increased hardness on the other hand. The high concentration leads to a higher number of cutting edges leading to a smaller depth of cut per grain which will result, for a given $Q_w$, in higher total...
forces. Furthermore during grinding the lower force per grain and the higher hardness make that a grain will stay longer in position, limiting the self-sharpening effect.

\[ \text{Figure 9-6: Grinding forces for different grinding wheels} \]

It should be noticed that the grinding forces for the D4-8 grinding wheel are measured while grinding at a reduced feed of \( v_f = 45 \text{ mm/min} \). At this reduced feed rate the forces are almost comparable to the V+2046 wheel. The very fine grain size leads to a high number of cutting edges making small chips, this leads to a low force per grain but this effect is overcompensated by the increased amount of cutting edges, leading effectively to high forces. It is because of the reduced feed rate that the forces still fall within the range of the D46 wheels.

The DMC and the V+2646 show comparable grinding forces, although the V+2646 starts at a lower force level directly after profiling.

The initially higher forces of the DMC grinding wheel are caused by a more closed wheel structure after crushing, this can be seen in Figure 9-7.

\[ \text{Figure 9-7: Metal bonded grinding wheel surface after crushing and after grinding} \]
In part a of the figure a diamond particle, graphite and the 2-phase binder material can be seen. The topography of the surface is rather smooth. In part b graphite is much less present and the diamond grain is much more exposed. Obviously the chipspace is created during the first millimeters of grinding length (free grinding), explaining the higher forces.

9.3.6 Grinding wheel wear

The wear of the grinding wheel is influenced by the preceding profiling operation. As the different grinding wheels are all profiled in the same way the wear curves bear information on the extent to which the grinding wheels are influenced by the profiling process. Based on the results of other profiling processes and the work on form crushing [Hess03] it is expected that the grinding wheels will show an increased wear directly after profiling. This wear compromises the profile accuracy and is therefore given special attention.

![Grinding wheel wear of different grinding wheels](image)

In Figure 9-8 wear curves are shown for the 5 different grinding wheels. These curves are fitted with a first order function. The slope of the curves represents the G-ratio of the grinding wheels. The point at which this fitted curve crosses the y-axis is the initial wear, which characterizes the damage to the grinding wheel structure due to the crushing operation. The calculated G-ratios and initial wear values are shown in Figure 9-9 and Table 9-5. Although the G-ratios vary largely, the initial wear values are small and do not vary much between the grinding wheels. Earlier experiments on a industry-standard profiling set-up [Derk05] showed initial wear values of 13 µm on a V2046 C100 wheel. This type of wheel is not included in the present experiment but can be placed in between the V+2646 and the V+2046 C150. These two wheels show initial wear of 3.3 and 2.5 µm respectively, which is significantly lower than the results of the industry-standard set-up.

The D4-8 wheel shows the highest initial wear. In theory the initial wear can be expected to be lower as the structure of the wheel is finer. A finer structure (smaller grains, smaller but more pores) would be able to stop crack growth in a shorter distance. However as argued before the
relative displacements (determined by the crushing depth $a_{ed} = 1 \mu m$ compared to the grain size and distance), are larger. Because of this in a single pass, not only the outer grain is dislodged but when doing so this grain comes into contact with the next layer of grains in the wheel, because the pore size and grains distance do not allow for this amount of displacement. This leads to deeper damage to the wheel structure than planned. This effect was theoretically predicted and experimentally verified by Klocke and Linke [Kloc08], with form dressing of conventional vitrified wheels. More extensive study at various grain and pore sizes and amounts should clarify the relation between these parameters and the crushing depth for form crushing of vitrified diamond wheels. In section 9.4 the influence of crushing depth $a_{ed}$ is studied in more detail for a single grinding wheel.

**Figure 9-9: Summary of results for different grinding wheels**

![Graph showing summary of results for different grinding wheels.](image)

<table>
<thead>
<tr>
<th>Grinding Wheel</th>
<th>$G_d$</th>
<th>$G$</th>
<th>Initial wear [$\mu m \cdot 10^{-2}$]</th>
<th>$F_{nd}$ [N/mm $\cdot 10^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>V+2646</td>
<td>446</td>
<td>235</td>
<td>3.3</td>
<td>22</td>
</tr>
<tr>
<td>D10U</td>
<td>399</td>
<td>468</td>
<td>2.5</td>
<td>13.7</td>
</tr>
<tr>
<td>V+2046L</td>
<td>265</td>
<td>1112</td>
<td>2.5</td>
<td>39.7</td>
</tr>
<tr>
<td>DMC</td>
<td>391</td>
<td>663</td>
<td>3.8</td>
<td>45.9</td>
</tr>
<tr>
<td>D4-8</td>
<td>5850*</td>
<td>230*</td>
<td>3.8*</td>
<td>51.4*</td>
</tr>
</tbody>
</table>

*D4-8: Grinding was done with 50% reduced feed rate and forces were evaluated at 10 $\mu m$ radial wear limit.

**Table 9-5: Summary of results for different grinding wheels**
9.3.7 Workpiece roughness

At determined intervals during the grinding operation imprints of the grinding wheel where made in graphite. These imprints have served to determine the wear of the grinding wheel. Furthermore the roughness of the worn area of the wheel is determined on the graphite. Due to the material structure of the graphite (porosity) the roughness values presented do not represent the workpiece roughness exactly, the values are too large. However from Figure 9-10 it can be seen that the roughness is high for all wheels at $L_s = 0$ mm. After a few mm grinding length the roughness has dropped significantly.

![Figure 9-10: Workpiece roughness in grinding for different wheels](image)

This is an indication that after dressing the grinding wheel surface contains debris from the dressing process. Particles of the grinding wheel layer that are crushed but not fully removed from the surface create a rougher surface in the graphite. When grinding the graphite the forces are so small that this debris is not removed. When grinding is started in the carbide the debris and loose grains will be roved in the first moments of grinding due to the grinding forces. These results show that cleaning of the grinding wheel surface during crushing is important. The debris will remain in the crushing layer and can make this layer denser, leading to higher forces and deeper damage to the grinding wheel.

9.4 Influence of crushing depth

As argued in section 9.1 the crushing depth influences profiling time and most likely grinding wheel integrity. In this section the influence of the crushing depth on form roll wear, crushing forces, grinding forces and grinding wheel wear is investigated. Therefore the V+2046 grinding wheel was profiled with different crushing depth $\delta_{cr}$ ranging from 1 to 6 $\mu$m. In every experiment a grinding wheel layer of about 150 $\mu$m was removed to remove the influence of the preceding experiment, followed by a grinding operation in tungsten carbide for $L_s = 100$ mm. Before every new experiment the form roll was reground to avoid an influence of the progressing wear of the form roll. All other parameters were the same as mentioned in Table 9-4.
9.4.1 Form roll wear

Increase of the depth of cut in dressing, \( a_{ed} \), will lead, for a given removed volume of grinding wheel material, \( V_w \), to a decrease in the contact time between grinding wheel and form roll: less dressing passes are needed to remove the material. Microslip on the other hand will increase. It seems also plausible that the crushing forces will increase, as the tool enters deeper into the wheel surface. The wear results of the form roll for varying crushing depth, Figure 9-11 indicate that higher crushing depth leads to less form roll wear. This indicates that contact time dominates the increase of microslip and crushing forces. The \( G_d \)-ratios based on these measurements are shown in Table 9-6 and show a 68 % increase in \( G_d \)-ratio when increasing the crushing depth from 1 to 6 µm.

![Figure 9-11: Form roll wear for different depth of cut \( a_{ed} \)](image)

9.4.2 Crushing normal forces

The normal forces in crushing are shown in Figure 9-12, shown is a filtered graph of the force values to make the data more readable. The original data can be found in Appendix B. For every value of \( a_{ed} \) a newly ground form roll was used. All 4 curves show an increase of the forces when the cumulative crushing depth increases. This can be explained by the wear of the form roll. When dressing is started with a new form roll the contact width \( b_d \) increases with progressing radial wear. This increase in contact width will lead to higher crushing forces. Furthermore the repeated crushing can close the surface of the grinding wheel with debris, leading to a more compact surface that is harder to crush. The sharp peaks in the signal are caused by thermal distortions between sets of dressing passes. The variance on the measured signals is rather large and the influence of the crushing depth is small, a light increase of the crushing forces with the crushing depth seems to be present. In Table 9-6 the forces averaged over the last 24 µm crushing depth in Figure 9-12 are shown. When increasing the crushing depth from 1 to 6 µm the crushing normal force increases by 28%.
Grinding forces

During crushing the grinding wheel surface is created. The resulting topography and integrity of the grinding wheel surface generates the workpiece surface roughness, the grinding forces and determines the grinding wheel wear. The grinding forces, shown in Figure 9-13, indicate that the grinding wheel behaves “sharper” with increasing crushing depth, what can be seen from the decreasing forces for increasing depth of cut. The larger crushing depth removes larger parts from the grinding wheel. This results in a rougher and therefore sharper grinding wheel surface. This leads to a smaller amount of active cutting edges and therefore larger chips. For the same specific material removal rate, $Q_w'$, this will lead to a smaller total grinding force. The increase of the grinding forces over the grinding length, $L_s$, can be explained by an increase in the total number of active edges due to wheel wear and dulling of the active grains. Directly after dressing the grains in the wheel are all new and sharp. However the outer layer of the grinding wheel will be damaged, resulting in lower grain holding forces. This effectively means that the grinding wheel will act “softer”, resulting in reduced grinding forces. When grinding would be continued significantly beyond $L_s = 100$ mm the forces should all reach a comparable level as the influence of the dressing operation is removed by the progressing wear of the grinding wheel. In Table 9-6 the forces extrapolated to $L_s = 1$ mm are shown. When increasing the crushing depth from 1 to 6 µm the normal and feed forces decrease with 47% and 43% respectively.
9.4.4 Grinding wheel wear

The grinding wheel wear clearly shows the increased damage to the grinding wheel structure at increased crushing depth (Figure 9-14), this is also supported by the measured grinding forces in the previous section. Most clearly visible is the increase in the initial wear, but also the slope of the wear curves increases, indicating an influence of the crushing depth on the G-ratio. Again for increased $L_s$ the G-ratios should converge to the same values. For profiled grinding this is however less relevant as by that time the profile accuracy will, in most cases, have deteriorated significantly and reprofiling is necessary. In Table 9-6 the initial wear values and G-ratios are shown: when increasing the crushing depth from 1 to 6 $\mu$m the initial wear increases by 67% and the G-ratio (calculated over $L_s = 100$ mm) decreases by 42%. 

Figure 9-13: Grinding forces for varying crushing depth

Figure 9-14: Grinding wheel wear for varying crushing depth
9.4.5 Workpiece roughness

The roughness was measured in the same way as explained in 9.3.7 and is shown in Figure 9-15.

![Figure 9-15: Workpiece roughness for varying $a_{ed}$](image)

The workpiece roughness Ra increases for higher values of the crushing depth, $a_{ed}$. The workpiece roughness Rz was also measured but shows a less clear trend. This is due to the fact that the porosity of the graphite on which is measured strongly influences the Rz values and less the Ra values.

9.4.6 Summary and conclusions

The effect of increasing crushing depth is pronounced; form roll wear decreases strongly, crushing forces increase only slightly, grinding forces decrease strongly and the grinding wheel wear increases significantly. This motivates the use of high crushing depth when efficient material removal of the grinding wheel is needed. On the other hand when maximum grinding wheel integrity and workpiece quality (low roughness and high accuracy) is needed the crushing depth should be kept low.

In practice this results in a preprofiling operation in which the profile is quickly and efficiently created in the grinding wheel. After this operation the profiling should be finished with several profiling passes at reduced crushing depth to remove the damaged outer layer of the grinding wheel and realize maximum profile integrity.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 µm</td>
<td>343</td>
<td>6.4</td>
<td>2.4</td>
<td>396</td>
<td>18.8</td>
<td>4.0</td>
<td>0.32</td>
</tr>
<tr>
<td>2 µm</td>
<td>462</td>
<td>6.5</td>
<td>2.6</td>
<td>332</td>
<td>13.8</td>
<td>3.0</td>
<td>0.39</td>
</tr>
<tr>
<td>4 µm</td>
<td>466</td>
<td>7.3</td>
<td>3.5</td>
<td>294</td>
<td>10.9</td>
<td>2.4</td>
<td>0.39</td>
</tr>
<tr>
<td>6 µm</td>
<td>576</td>
<td>8.2</td>
<td>4.0</td>
<td>228</td>
<td>9.9</td>
<td>2.3</td>
<td>0.45</td>
</tr>
</tbody>
</table>

*a* averaged over last 24 µm removal of grinding wheel layer *b* evaluated at $L_s = 10$ mm

Table 9-6: Summary of influences of varying crushing depth
9.5 Influence of contact width on crushability

In the preceding section the influence of the contact width on the results was neglected. For every experiment a fresh reground form roll was used. However when the form roll is used it wears and the crushing contact width increases. To study the influence of this increase an experiment was set up in which the grinding wheel was alternating crushed and used for grinding. Crushing forces as well as grinding forces and grinding wheel wear were recorded. The results are presented in the following. The radial form roll wear determines the contact width. The overlap ratio in dressing, $U_{dr}$, is set at the value of 2, based on the initial state of the form roll. This implies that with progressing wear the effective overlap ratio increases because the feed rate in crushing, $v_{fad}$, is kept constant while the contact width increases. This has been a deliberate choice as it represents the situation in which this operation will be used in practice. Secondly research by Hessel [Hess03] has shown a small influence of the overlap ratio.

9.5.1 Crushing normal forces

The crushing forces itself are measured and shown in Figure 9-16. However these are the total forces, to study the influence of the contact width these should be compared with the specific forces, that is the total crushing normal forces divided by the actual contact width in crushing. The contact width in crushing does however vary. To be able to convert all the values of Figure 9-16 to specific forces, the relation between the amount of crushing passes, $a_{ed,cum}$, and $b_d$ should be known.

![Figure 9-16: Crushing normal forces for varying crushing contact width](image)

During the experiments only few measurements of the radial wear, that enable calculation of $b_d$, were taken at discrete intervals. In Figure 9-17 two sets of data are plotted. The experiments were performed on the same grinding wheel with identical crushing parameters. Via curve fitting a function describing these curves is determined and this function is used to calculate the specific crushing forces. As can be seen at $a_{ed,cum} = 0 \, \mu m$ the contact width is about 30 \, \mu m, this is because
the contact width is determined by the wear flat (which is 0 at \( a_{ed,cum} = 0 \)) and the depth of cut in crushing (\( a_{ed} = 1 \mu m \) in this case).

**Fitted rational function:**
\[
y = \frac{(p_1 \cdot x^3 + p_2 \cdot x^2 + p_3 \cdot x + p_4)}{(x + q_1)}
\]

**Figure 9-17: Relation between cumulative crushing depth and the crushing contact width**

In Figure 9-18 and Figure 9-19 the specific crushing forces are shown against \( a_{ed,cum} \) and \( b_d \) respectively, for the two repetitions on the V+2646 grinding wheel. The specific forces decrease with increasing \( a_{ed} \) and increasing \( b_d \). The values below \( a_{ed,cum} = 30 \mu m \) are not considered here because the measurement errors lead to too large variations in this range. Furthermore the initial phase is also disturbed by the fact that the pretension, that has to built up between form roll and grinding wheel, is not fully developed leading to forces, but no (or limited) material removal. The values measured for \( F'_{nd} \) are therefore not representative during these passes.

**Figure 9-18: Specific normal crushing forces against \( a_{ed,cum} \)**
The decrease in the specific forces can be understood when the overlap ratio, $U_d$, is considered. With progressing wear $U_d$ increases. The material removal rate is determined by $v_{rd}$ and $a_{rd}$ and is therefore constant. This means that the normal force is composed of a component needed to “machine” the material and a pretension component on the rest of $b_d$, which is not removing material, but only rolling on the grinding wheel surface without exceeding the stress levels needed for material removal. When $U_d$ increases, the ratio between the part of $b_d$ that removes material and the part that only rolls, decreases, leading to a lower specific force. Based on the preceding discussion a relation of the form:

$$F'_{nd,crush} = F'_{nd,crush} - \frac{b_d}{b_d + b_d - b_d - b_d} (b_d - b_d - b_d - b_d) - F'_{nd,roll} (U_d - U_d - U_d - U_d)$$

is expected to be present. This is however a simplified relation as it assumes $F'_{nd,crush}$ and $F'_{nd,roll}$ to be constants, which might not be the case. From Equation 3.2 it is known that:

$$U_d = \frac{b_d}{b_d}$$

It can be seen that the relation between $F'_{nd}$ and $b_d$ is expected to be of the form: $y = a + bx$.

Given the limited amount of data and the large measurement error this assumption cannot be tested and the trends shown in the graph are simple linear curves and only indicative. More extensive experiments would be needed to investigate the influence of $b_d$ and to test the validity of Equation 9-1.

### 9.5.2 Initial grinding wheel wear

The wear of the grinding wheel is influenced by the contact width in crushing as can be seen from Figure 9-20. Initial wear increases with increasing contact width. The G-ratios measured were
evaluated over $L_s = 100$ mm and seem to drop for increasing contact width, as would be expected. From these measurements it can therefore be concluded that a larger contact width in crushing leads to more damage to the grinding wheel structure. This can be explained by the increase of the overlap ratio; the grains that are left in the grinding wheel will be touched by the grinding wheel $U_d$ 1 times. These contacts take place with a little lower force (determined by $F_{n,d,\text{int}}$, see previous section) but these forces can still induce damage to the grinding layer, resulting in increased wear.

![Graph](image)

*Figure 9-20: Initial wear and G-ratios for varying contact width in crushing*

### 9.5.3 Grinding forces

The grinding forces showed already large variations in the measurements. This variance makes it difficult to isolate the influence of the contact width in crushing based on a single set of measurements. Figure 9-21 shows these measured specific grinding forces. Based on these measurements it seems that the contact width in dressing has no significant influence on the grinding forces.

![Graph](image)

*Figure 9-21: Grinding forces for varying contact width in dressing*
9.5.4 Summary and conclusion

The experiments in the preceding sections have indicated that an increased contact width has a negative influence on the integrity of the grinding wheel, but little influence on the grinding forces, compared to the variance of these forces. The total crushing normal forces are not influenced significantly by the contact width, in the range measured. However the specific crushing forces decrease due to the increase of the overlap ratio with progressing wear. The influence on the form roll wear is not shown as this would require evaluation of incremental wear data which is too sensitive for measurement errors. It can however be expected that, because \( U_d \) increases with increasing \( b_d \), there is more contact time for the given material removal, leading to lower \( G_d \) values of the form rolls used. Adjusting the axial feed speed in dressing, \( v_{fad} \), could eliminate this effect. However this would, with some extra effort, be realizable on straight profiles but is not practical on more complex profiles as the effective contact width is dependent on both the position along the profile and the form roll wear.

9.6 Summary and conclusion

The influence of grinding wheel composition has been studied and indicated that a wide variety of grinding wheels can be profiled with form crushing, including a bronze bonded wheel and a vitrified very fine grain D4-8 wheel. The wear of the form roll is strongly influenced by the grain size which is shown by a very high \( G_d \) ratio of the D4-8 wheel. The damage to the grinding wheel after crushing was measured and was limited: for all wheels the initial wear was less than 4 \( \mu m \).

Depth of cut in crushing showed to have a significant influence both on the grinding wheel integrity as on the form roll wear, resulting in the advice to preprofile with high and finish with small depth of cut to remove the damaged layer.

The contact width showed an influence on the (specific) crushing forces and a small effect on the grinding performance. Overall its influence can be considered small.
10 Case studies

This chapter will introduce some case studies on the application of form crushing profiling. First the result of a profile created by form crushing in a large vitrified SiC grinding wheel is shown in section 10.1. Following in 10.2 a D46 diamond grinding wheel is profiled, which is a typical application for the form crushing process. To push the limits of the crushing process further a vitrified D4-8 grinding wheel was profiled with a 15-fold radius profile, section 10.3.

10.1 Saw tooth profile in SiC wheel

From industry the need to create a profile as indicated in Figure 10-1 was formulated. An initial study to explore the possibility to use profile grinding was performed.

Figure 10-1: Saw tooth profile: profile dimensions (upper), ground workpiece (lower)
This product has to be produced in large numbers with high accuracy. The profile consists of 26 teeth that are spaced at 1.25 mm. The profile height is 0.77 mm and the top angle was 42 degrees and the top radius 100 µm.

The workpiece consisted of an austenitic stainless steel strip with a thickness of 0.1 mm. Preference was given to the use of a conventional vitrified silicon carbide grinding wheel. This was based on the lower procurement cost and the profilability of the grinding wheel. To profile the wheel form dressing would have been possible but would have led to more wear of the form roll compared to form crushing, compromising the accuracy. Profile dressing or -crushing where not an option due to the high (initial) cost and long delivery time of the dedicated tooling.

The grain size of the used crushable vitrified SiC grinding wheel with high porosity was in the range of 25-50 µm. More details can be found in Table 10-1.

<table>
<thead>
<tr>
<th>Grinding wheel</th>
<th>Form roll</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Winterthur</td>
</tr>
<tr>
<td>Wheel specification</td>
<td>11C 250/350 F/G20 VP030G</td>
</tr>
<tr>
<td>Wheel shape</td>
<td>1A1</td>
</tr>
<tr>
<td>Abrasive type</td>
<td>SiC</td>
</tr>
<tr>
<td>Grain size</td>
<td>25-50 µm</td>
</tr>
<tr>
<td>d_i</td>
<td>360 mm</td>
</tr>
<tr>
<td>b_i</td>
<td>40 mm</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Set CVD diamond</td>
</tr>
<tr>
<td>R_tip</td>
<td>120 mm</td>
</tr>
<tr>
<td>Workpiece</td>
<td></td>
</tr>
<tr>
<td>Workpiece designation</td>
<td>Sandvik Nanoflex</td>
</tr>
<tr>
<td>Material</td>
<td>Austenitic stainless steel</td>
</tr>
<tr>
<td>Material thickness</td>
<td>0.1 mm (stacked to 3 mm)</td>
</tr>
</tbody>
</table>

Table 10-1: Grinding wheel form roll and workpiece properties for saw tooth profile experiment

The form roll used was of the same type as used for the experiments in the previous chapters containing a tip radius of \( R_{\text{tip}} = 100 \, \mu\text{m} \). The 0.1 mm thin workpieces were stacked with 30 pieces together to create an effective width of the workpiece of 3 mm. For the grinding operation creep feed grinding was selected to reduce the load on the grains and thereby minimizing the profile wear.

The 0.77 mm deep profile was created out of the straight unprofiled (1A1) grinding wheel. The demanded profile is shown in the upper part of Figure 10-1. For clarity only three teeth are shown, while the actual profile contained 26 teeth. The sides of the teeth are steep, and have an angle of 42 degrees while the form roll had a top angle of 40 degrees. Profiling was done in two steps: preprofiling and reprofiling. To create the initial profile a larger depth of cut of \( a_{\text{cut}} = 5 \, \mu\text{m} \) was used to accelerate the process. The preprofiling time amounted to 160 minutes. After the preprofiling, reprofiling was done with a reduced crushing depth of \( a_{\text{cr}} = 2 \, \mu\text{m} \) to reduce the damage to the grinding wheel structure. This took only a few minutes. During profiling the profile was created by following the profile contour with the form roll from right to left, as indicated in the upper part of
Figure 10-1. The used profiling parameters are shown in Table 10-2. The speeds in grinding and profiling were chosen the same to avoid a different dynamic behavior of the machine.

<table>
<thead>
<tr>
<th>Profiling</th>
<th>Gridding</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v_{sd})</td>
<td>28 m/s</td>
</tr>
<tr>
<td>(v_{fa})</td>
<td>51 mm/min</td>
</tr>
<tr>
<td>(a_{ed}) (preprofiling)</td>
<td>5 (\mu)m</td>
</tr>
<tr>
<td>(a_{ed}) (reprofiling)</td>
<td>2 (\mu)m</td>
</tr>
<tr>
<td>Profile depth</td>
<td>0.77 mm</td>
</tr>
<tr>
<td>Profile width</td>
<td>40 mm</td>
</tr>
</tbody>
</table>

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(v_f)</td>
<td>28 m/s</td>
</tr>
<tr>
<td>(a_e)</td>
<td>1 mm</td>
</tr>
<tr>
<td>(v_{f1})</td>
<td>100 mm/min</td>
</tr>
<tr>
<td>Coolant</td>
<td>Synthetic water soluble, 4% conc.</td>
</tr>
</tbody>
</table>

Table 10-2: Grinding and profiling parameters for saw tooth profile experiment

The produced profile showed good profile accuracy in the inner corners, there the radius of the form roll is directly transferred to the grinding wheel. On the outer corners some rounding can be seen, lower part of Figure 10-1, the picture was taken after a grinding length of \(L_s = 10\) mm. The rounding can therefore be partly contributed to wear and partly to the grinding wheel grain size. The corner rounding was measured to have a 70 \(\mu\)m radius which can be considered low compared to the average grain size. The accuracy of the internal radii was within 3 \(\mu\)m of the top radius of the form roll.

The wear area of the form roll was measured to be 13160 \(\mu\)m\(^2\) resulting in a wear volume of 4.96 mm\(^3\). Because of the horizontal and steep faces of the profile the wear was distributed more evenly over the form roll radius than with the experiments in chapter 9. Therefore the radius of the form roll was useable even with considerable wear. The volume removed of the grinding wheel was 20000 mm\(^3\) resulting in a \(G_d\) ratio of 4000. This relatively low wear ratio can be explained by the fact that the control system for the form roll used in this experiment, was not as advanced as the system used for the experiments in chapter 9. The form roll was used in constant torque control without feedback or updating of the torque value. This resulted in a speed mismatch, and therefore slip, every time contact was established. Because the profile, with its 26 teeth, was created out of a straight profiled wheel, this slip occurred 26 times per pass until the full profile was created in the grinding wheel. As the wear ratios are still much higher than in crush profiling of diamond wheels, SiC wheels are not a valid option for regrinding of the diamond form rolls. Therefore diamond was used for regrinding of the diamond form rolls in chapter 8. For profiling of conventional grinding wheels with high accuracy demands and small profile details form crushing can be an attractive method.

10.2 D46 triangle profile

To investigate the capabilities of an actual diamond profiling cycle, a D46 V+2646 wheel was profiled with a profile that can indicate the performance on both external and internal radii.
Internal radii on the grinding wheel are rather tough as the grains are supported for more than 180 degrees by bond material. The difficulty with inner radii is generally that the smallest achievable radius is determined by the radius on the form roll. If the form roll is used to make the smallest radius, the roll is simply imprinted in the grinding wheel. When this is done the wear of the form roll is directly transferred to that radius. Outer radii are not limited by the radius of the form roll. In theory a sharp outer radius can be made even with a large form roll tip radius. The difficulty with outer radii is however that for small radii the radius is formed by few grains that are supported by less than 180 degrees of bond, leading to lower grain holding forces and therefore increased wear. The profile shown in Figure 10-2 was chosen to investigate both these situations. The four triangles have a radius at their top of 115 µm. This was the top radius of the form roll. Between the two triangles in the middle there is a 90 degree outer corner that is the limit situation for an outer radius: the smallest radius achievable for this combination of grinding wheel and profiling method can be investigated here. The top angle of the form roll was 60 degrees so the flanks are traversed (not made by plunging). The axial feed speed $v_{ad}$ was determined based on a $U_d$ value of 2, and $v_{sd} = 25$ m/s resulting in an axial feed speed of around 105 mm/min. The $U_d$ value was deliberately kept low to decrease profiling time as argued in section 9.1. The profile was traversed every pass from the same direction (from right to left, as indicated in Figure 10-2). This was necessary because the grinding machine has difficulty repeating the same trajectory in the opposite direction, as was described in 5.1.1.

The full profile was created out of a fresh 1A grinding wheel with a diameter of $d_s = 70$ mm and width $b_d = 8$ mm, so there was originally no profile present in the wheel. After mounting the grinding wheel, profiling of the wheel was started until full contact along the whole profile was achieved, this was monitored with the acoustic emission system.

During the preprofiling phase the rough shape of the profile is created in the grinding wheel. Reduction of profiling time is the most important demand here. Therefore a relatively large crushing
depth of $a_{ed} = 4 \, \mu m$ is used. To remove $30 \, \mu m$ run-out and create the $450 \, \mu m$ deep profile an $a_{ed, tot} = 620 \, \mu m$ was used, this cost about 30 minutes profiling time. The large crushing depth will however compromise the profile integrity as argued in chapter 9. The form roll showed some wear after preprofiling: the radial wear was measured to be $18 \, \mu m$. Therefore the form roll was reground on the machine. Regrinding of the form roll was done with a different diamond grinding wheel and this process has been described in chapter 8. In this case regrinding took less than 30 min as the form roll wear was limited. The top radius created on the form roll was $R_{top} = 115 \, \mu m$. With the new form roll the grinding wheel was profiled again, this time with a small crushing depth of $a_{ed} = 1 \, \mu m$ and $a_{ed, tot} = 20 \, \mu m$, to reduce the damaged layer and to increase the profile integrity, this took 3 minutes. Synchronization along the full profile was achieved as was shown for a comparable profile in section 7.6. Altogether the creation of the profile costed about 120 min due to the time spent an adjusting of the form roll and other auxiliary tasks.

To test the integrity of the profiled wheel a creep feed grinding operation with $L_s = 200 \, mm$ was done with a depth of cut $a_e = 0.6 \, mm$ and $v_f = 90 \, mm/min$. The workpiece material was a fine-grain cemented Tungsten Carbide as detailed in chapter 5. The results showed no measurable wear of the profile depth and the radii of $115 \, \mu m$ after 200 mm grinding length. The measurement accuracy was +/- 1 $\mu m$. The 90 degree outer corner located in the centre of the profile had a radius of $36 \, \mu m$ just after starting grinding, which developed to $59 \, \mu m$ at 200 mm grinding length. In Figure 10-3 the wear of this outer radius and the height of the lowest point of this radius to the base level of the profile are shown on the left. Normally several times the average grain radius is taken as the minimum radius that should be profiled on a grinding wheel. Considering the average grain size of $46 \, \mu m$ these results show that the damage to the grinding wheel is at an acceptable low level.

![Figure 10-3: Profile wear and grinding forces D46 triangle profile](image)

On the right side of Figure 10-3 the grinding forces are shown, during the first 50 mm the normal grinding forces are lower. After these initial 50 mm the forces stabilize. This behavior was also seen in other experiments with the V+2646 specification. A picture of the part made with this profile is shown in Figure 10-4, it was made by rotating the workpiece by 90 degrees after grinding and
grinding it again at the same depth of cut. The result is a set of pyramids with a base of 1 mm². In Figure 10-4 on the right an image of the produced pyramids, created with a white light interferometer is shown. On the top of the pyramids the radius of the form roll is visible.

Figure 10-4: Pyramids ground in WC-Co with D46 wheel.

Conclusively it can be stated that the intended profile was created in the grinding wheel with high accuracy. The largest deviations arrived from the grain size of the grinding wheel and constitute the limit of this profiling operation.

10.3 D4-8 lenticular profile

To test the stability of profiles in ultra fine-grain diamond wheels, a D4-8 grinding wheel was profiled with a lenticular profile [Derk08]. This profile is shown in Figure 10-5 and consists of alternating radii of 510 and 50 µm. This type of profiles is for example used in the advertising industry to add 3-D, or motion effects to billboards. Every 510 µm radius in the profile is actually a (line-shaped) lens. Because the surface of the lenses should be of high quality and the small details in the profile a small grain size is needed. The D4-8 grain size is one of the smallest sizes used in grinding wheels, available on the market.

Figure 10-5: Lenticular profile
Use was made of a large grinding wheel with a diameter of \(d_s = 338\) mm and width \(b_s = 10\) mm, directly mounted on the main spindle of the grinding machine. The specification of the wheel was: Norton D4/8 MIC – K2V5, which is the same specification as the D4-8 wheel used in chapter 9. The difference was the diameter used: \(d_s = 340\) mm. Because of its size this wheel was mounted directly on the main spindle of the grinding machine.

To keep the impact on the grinding wheel during profiling low, a crushing depth of \(a_w = 1\) µm per pass was used. The overlap ratio is kept low at \(U_d = 2\) to reduce profiling time and reduce form roll wear, resulting in an axial feed speed of \(v_{fad} = 19\) mm/min. Profiling was done at grinding speed: \(v_{sd} = v_s = 25\) m/s. After mounting the grinding wheel the run-out was measured at 30 µm. From Figure 10-5, the depth of the profile is 60 µm. In theory 90 profiling passes would be needed to create the profile. For certainty 100 passes are profiled, this took about 73 minutes. The form roll was measured before profiling to have a radius of 90 µm, after profiling a radial wear of 6 µm was measured.

The normal crushing forces are measured during profiling, the results of the last pass are shown in Figure 10-6. In this force profile the actual geometrical profile can be recognized. The force profile starts and ends with a section with relatively constant forces: crushing of a straight, flat surface. Then the forces fall and rise alternating. The highest force is reached halfway the 510 µm radius.

![Figure 10-6: Force and AE signals for the last dressing pass of the lenticular profile](image)

Three effects are seen: 1) the overall force level is high, 2) the forces vary strongly on the curved sections and 3) the forces increase over the width of the profile. To understand the development of the forces the contact width should be considered first. On the straight parts of the profile the contact width (for the given radius and wear of the roll) was: \(b_d = 65\) µm. In chapter 9 a specific normal crushing force of \(F'_{nd} = 51\) N/mm was measured for the grinding wheel specification used here. This leads to an expected force of 3.3 N. As can be seen in Figure 10-6, left the forces are at a much higher level of over 10 N.

A source for the varying forces on the curved sections can be found when looking at the contact conditions on these sections. When considering the form roll top radius of 90 µm (convex), the
concave 510 µm radius and convex 50 µm radius it becomes clear that the contact width will vary. In the convex-convex situation the contact width will be small, as illustrated in Figure 10-7a, on the other hand in the concave-convex situation the contact width will be larger, Figure 10-7b.

![Diagram showing contact width in convex-convex and convex-concave situations](image)

This contact width can be calculated by:

\[
b_d = \frac{1}{d_{\text{geo}}} \sqrt{4 \cdot d_{\text{geo}}^2 \cdot R_{\text{top}}^2 - (d_{\text{geo}}^2 - R_{\text{prof}}^2 + R_{\text{top}}^2)^2}
\]

(10-1)

In which \(d\) is defined by:

\[
d_{\text{geo}} = R_{\text{top}} + R_{\text{prof}} - a_e
\]

(10-2)

The theoretical contact widths for these two extreme situations are: 16 µm and 29 µm respectively, a ratio of about 2. However for the particular situation described here the form roll was worn. When a wear flat builds on the form roll the effective form roll radius increases and the difference between the two contact situations increases (because the effective top radius becomes closer to the convex radius on the grinding wheel). This (partly) explains the higher forces in the convex part of the profile.

Another difference along the profile explaining the increase of the forces in the 510 µm radii is that the cumulative crushing depth along the lower sections of the profile is smaller than on the higher (deeper) sections. It can be the case that due to continued dressing in these areas the wheel structure is compacted leading to higher crushing forces there.

The grinding wheel used was also larger than the wheel used for the experiments in chapter 9. This larger wheel radius leads to a larger contact length. The geometric contact length in grinding is defined as [Mari07]:

\[
l_g = \sqrt{a_{ed} \cdot d_{eq}}
\]

(10-3)

Where \(d_{eq}\) is defined as:
For the given form roll (dr = 120 mm) and grinding wheels (ds = 100 resp. 340 mm) this leads to contact lengths of 233 resp. 298 µm (28% larger). The influence of the contact length is not studied in this work. However it seems unlikely that this would completely explain the large difference between the forces measured in this experiment and the results in chapter 9. It is therefore expected that the used grinding wheel had different properties that the wheel used in chapter 9, even though the specification was the same.

Another effect that is seen in Figure 10-6 is that the forces increase along a profiling pass. This increase is also visible in the AE signal and therefore not attributable to drift of the force measuring system. The increase in the forces can not be caused by a change in the crushing depth as 1) in every crushing pass the development of the forces is the same and 2) the results shown are for the 100th pass so the initial state of the grinding wheel should have no influence anymore. It is therefore expected that the rising forces are caused by inhomogeneity of the grinding wheel. This can happen during the pressing stage of the manufacturing process.

Concluding about the measured forces it can be said that the forces are not representative for the given grinding wheel specification. It is most likely that the properties of the wheel where different from the wheel used in chapter 9.

When the speed curves are studied, see Figure 10-8, it can be seen that the measurement variance is close to the speed changes that are expected to be measured. The expected variation in the speed is determined by the relation between the relative profile depth, defined as the ratio of the profile depth hp and the grinding wheel radius ds/2, times the crushing speed vsd. For the lenticular profile this leads to a speed variation of:

\[
\Delta v = h_{p,rel} \cdot v_{sd} = \frac{2 \cdot h_p}{d_s} \cdot v_{sd} = \frac{2 \cdot 0.06 \cdot 10^{-3}}{338 \cdot 10^{-3}} \cdot 25 = 8.9 \cdot 10^{-3} \text{[m/s]} \tag{10-5}
\]

\[
d_{eq} = \frac{d_s \cdot d_r}{d_s + d_r}
\tag{10-4}
\]
Creep feed grinding was done in WC-Co for 800 mm at a feed \( v_f = 45 \text{ mm/min} \) and depth \( a_e = 0.2 \text{ mm} \). The result of this grinding operation is shown in Figure 10-10. After 800 mm no wear on the profile radii (Figure 10-9), and height could be measured. As the profile contains multiple radii they are all measured and the result is averaged. In the graphs this is indicated by the number of averages, \( n \). Also indicated is the variance within a set of \( n \) replications, represented by the standard deviation \( \sigma \), this was for all measurements below \( \sigma = 6 \text{ µm} \). The measured radii differ a little from the target values, this is caused by the fact that the form roll was worn a little. Effectively the form roll had a larger radius resulting on the large convex radii of the profile in a larger profile and on the small concave radii to a smaller value. With a reground form roll, or compensation of the tool trajectory this error can be removed. The surface roughness achieved was \( Ra = 0.05 \text{ µm} \) measured square to the grinding direction.

![Figure 10-9: Profile wear of the lenticular profile](image)

**Figure 10-9: Profile wear of the lenticular profile**

![Figure 10-10: Lenticular ground in WC-Co with D4-8 wheel.](image)

**Figure 10-10: Lenticular ground in WC-Co with D4-8 wheel.**

**10.4 Summary and conclusion**

Form crush profiling was shown to be capable of creating complex profiles in vitrified bonded grinding wheels. The created profiles are usable in grinding and show little wear, indicating that the damage to the grinding wheel is relatively small. The accuracy of the created profiles is mainly
determined by the wear of the form roll, which can be countered by regrinding the form roll. In that case high accuracy profiles can be made. This result indicates that there is a balance between accuracy and economy of the process. For extreme high accuracy profiling tasks automated regrinding of the form roll on the machine can be the only practical and economical solution.
11 Final conclusions and recommendations

Grinding with super-abrasive tools has become a common technology to manufacture parts made of hard materials like cemented tungsten carbides and ceramics. One of the main advantages of grinding is the high accuracy that can be achieved. The condition of the grinding wheel is of utmost importance for the performance of the process. Conditioning of diamond grinding wheels has been the subject of many studies but generating shapes in a grinding wheel (profiling) with high accuracy in a flexible way is an issue that is not generally solved yet.

In the course of this work a profiling system has been developed that enables the high-accuracy and flexible profiling of diamond grinding wheels. The key factors in this system are:

- A newly developed profiling device with increased stiffness, damping and control accuracy to enable the successful implementation of form crush profiling.
- A new method for synchronization of the form roll with the grinding wheel to guarantee optimal synchronization while at the same time reducing operator intervention and communication with the machine tool control.
- Reprofiling of the diamond form rolls on the grinding machine leading to increased accuracy and flexibility while at the same time offering potential for cost savings.

Due to this system it was proven possible to profile vitrified grinding wheels and also a class of bronze bonded diamond grinding wheels with high accuracy. Even very fine-grained wheels with average grain sizes of 4-8 µm where profiled without difficulty, while in earlier researches this showed to be problematic. With these smaller grain sizes, smaller details can be created in the profiles. The accuracies achieved are highly dependent on the grinding wheel properties as these properties influence the two main factors determining accuracy: 1) damage to the grinding wheel, leading to initial grinding wheel wear and 2) the wear of the form roll, leading to a deviation in the actual toolpath. The damage induced to the grinding wheel was different for varying wheel specification but was for all wheels below 4 µm. The wear of the form roll was influenced strongly by the grain size of the abrasives in the grinding wheel: smaller grains lead to reduced wear.

The synchronization of the form roll was taken up and this problem was solved effectively. The suggested system can be implemented rather straightforward and reduces the system complexity, while ensuring optimal synchronization. Taking this control system as a starting point it would be interesting to investigate the relation between the slip and form roll wear as there is little information available on this relation.
Regrinding of diamond form rolls on the machine proved both possible and economically viable. However this process can be further optimized leading to an even more attractive process. Further automation of this process would be an important step towards fully autonomous profiled grinding.

The influence of the type of cooling fluid and a cleaning process (e.g. a high pressure nozzle) on the form crushing operation have not been addressed in this work and are still open for further research.

Form crush profiling can be applied in industry for complex profiling tasks with high demands on the accuracy. A crush profiling system can also be used for rotary diamond dressing and is in that way able to profile a wide variety of grinding wheels, ranging from conventional to super-abrasive wheels. This gives the end-user the possibility to adapt the grinding wheel to the grinding task at hand.
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Appendix A: Hydrostatic bearing design calculations

In the design of the hydrostatic bearings a lot of choices have to be made. Some are determined by external constraints, like interfaces with other parts, available space etc. Some can be chosen to influence the performance of the bearing. The calculation of the radial bearings below is based on the bearing optimization of Kraakman and further details can be found in [Kra77], the calculations of the axial bearing are more straightforward and more information can be found in a textbook on bearing design e.g. [Bee04].

An important parameter is the gap clearance, $h_0$. With decreasing gap clearance the power consumption (of the pump supplying the pressurized fluid) of the bearing decreases with $(h_0)^3$ and the stiffness and bearing friction increase linearly. The main constraint on choosing $h_0$ is however determined by the risk of clogging of the bearing gaps with pollution particles. In practice 20 μm has shown to be a good value as it can handle pollution particles up to about 6 um, which is a value that can reasonably be filtered out with available filters.

Another design parameter is the viscosity of the hydraulic fluid. As explained in chapter 6 the water based grinding liquid will be used, which contains 96% water therefore the viscosity of water is used in the calculations.

The pressure of the hydraulic fluid is related proportional to the flow, power consumption and the stiffness of the bearing. The type of fluid pump available for this application could deliver pressures up to 5 MPa. A design pressure of 3.5 MPa is set to provide for some margin to increase the stiffness of the bearing during use to investigate its influence.

\begin{align*}
h_0 &= 20 \cdot 10^{-6} \text{ [m]} & \text{Nominal bearing gap height} \\
p_s &= 35 \cdot 10^5 \text{ [Pa]} & \text{Hydraulic supply pressure} \\
p_a &= 0 \cdot 10^5 \text{ [Pa]} & \text{Ambient pressure} \\
\eta &= 0.001 \text{ [N·s/m$^2$]} & \text{Viscosity of hydraulic fluid} \\
\text{rpm} &= 6000 \text{ [-]} & \text{Nominal bearing speed}
\end{align*}
Radial bearing design

The radial bearing has to fit the design space of the dressing unit. Therefore a maximum effective bearing diameter of 34 mm was set. For assembly reasons and to provide pre-tension for the axial bearing (see section 6.4.2) the diameter of the second radial bearing is chosen smaller. The width of the bearings is also constrained by the design space.

The influence of the amount of bearing pockets was investigated in [Kra77] and it was shown that ideally more pockets lead to higher stiffness. However due to losses on the bearing lands and manufacturing effort 6 pockets is the practical optimum.

\[ n = 6 \quad [-] \quad \text{Amount of radial bearing pockets} \]

The parameters introduced below determine the geometry, and thereby the performance, of the bearing. Only the resulting bearing performance is calculated below, the optimization procedure can be found in [Kra77].

In Figure 11 a sketch of a single bearing pocket (indicated pocket number 1) is shown with some critical dimensions and the different flows in the bearing. The flows are indicated with dashed arrows and dimensions with solid lines. The flow into the restrictor pocket is guided to the opposing pocket, number 4, because there are 6 pockets. The calculations below are based on actual bearing dimensions and deviate somewhat from the most optimal values according to [Kra77]. The calculations below refer to a single bearing, not a single pocket. Also the calculations consider the bearing in an unloaded condition, resulting in equal pocket pressures in all pockets. Therefore the indication \( p_{r1} \) will be used to indicate the pocket pressure(s) in bearing 1, to simplify notation.

\[ B \]

\[ p_0, p_{ps}, p_{in1,1}, p_{in2,1}, p_{t}, p_{r4}, p_{out}, p_{f1} \]

Figure 11: Sketch of pocket 1 of a radial hydrostatic bearing with integrated restrictor
First a value has to be determined for the length of the exit bearing land of a pocket: \( l_1 \) (with the index 1 indicating bearing 1). As the gap height and pocket pressure are given (the optimal pocket pressure is half the supply pressure) this value basically determines the flow through the bearing.

**Radial bearing 1**

\[
B_1 = 30 \cdot 10^{-3} \quad [\text{m}] \quad \text{Width of radial bearing 1}
\]

\[
D_1 = 30 \cdot 10^{-3} \quad [\text{m}] \quad \text{Diameter of radial bearing 1}
\]

\[
l_1 = 2 \cdot 10^{-3} \quad [\text{m}] \quad \text{Chosen value of exit land length}
\]

\[
l_{t1} = 5.23 \cdot 10^{-3} \quad [\text{m}] \quad \text{Length of radial dividing land}
\]

\[
l_{\delta 1} = 9.7 \cdot 10^{-3} \quad [\text{m}] \quad \text{Length of axial dividing land}
\]

\[
l_{l1} = 0.5 \cdot 10^{-3} \quad [\text{m}] \quad \text{Length restrictor}
\]

Relative width of restrictor:

\[
\xi_1 = \frac{6.8}{60} \quad \text{(A-6)}
\]

\[
\Delta_1 = \frac{2 \cdot B_1 \cdot l_1}{D_1 \cdot l_{t1}} = 0.765 \quad \text{(A-7)}
\]

\[
\delta_1 = \frac{\delta l_1}{l_1} = 4.85 \quad \text{(A-8)}
\]

\[
\xi_1 = \frac{l_{l1}}{l_1} = 0.25 \quad \text{(A-9)}
\]

Given the above geometry the effective width of the bearing can be calculated:

\[
B_{eff1} = B_1 \frac{l_{l1}}{2} \cdot \xi_1 \cdot \delta_1 \cdot l_{l1} - 2 \cdot \xi_1 \cdot \xi_{\delta} \cdot \xi_1 \cdot l_{l1} \cdot \frac{1 - \xi_1}{2} \cdot (\xi_1 + \delta_1) \cdot l_{l1} = 0.028 \quad \text{(A-10)}
\]

This leads to the bearing stiffness expressed as:

\[
K_{rad1} = \frac{27}{4 \cdot \pi} \cdot \frac{p_s \cdot D_1 \cdot B_{eff1}}{\eta \cdot h_0} \left\{ \frac{1 - \frac{1 - \xi_1}{\delta_1}}{1 + \frac{3 \cdot \Delta_1}{2 \cdot \pi} + \frac{2 \cdot \xi_1}{\delta_1}} \right\} = 1.843 \cdot 10^4 \quad \text{(A-11)}
\]

\[\text{N/m radial stiffness of bearing 1.}\]

Now based on a volume balance the set of equations below holds and can be solved for the flows and the pocket pressure.

\[
Q_1 = Q_{in} + Q_{inleak} \quad \text{(A-12)}
\]

\[
Q_1 = \frac{p r_1 \cdot \pi \cdot D_1 \cdot h_0^3}{12 \cdot \eta \cdot l_1} \quad \text{(A-13)}
\]

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Applying equations (A-14) and (A-15), we find:

\[
Q_{in} = \frac{(ps - pr) \cdot \pi \cdot D_1 \cdot ho^3}{12 \cdot \eta \cdot \xi_1 \cdot l_1}
\]

\[
Q_{in\text{eak}} = \frac{(ps - pr) \cdot (1 - \xi_1) \cdot \pi \cdot D_1 \cdot ho^3}{12 \cdot \eta \cdot (\xi_1 \cdot l_1 + \delta_1 \cdot l_1)}
\]

Solving for \(Q_1\) and \(pr_1\) leads to: \(Q_1 = 4.238 \cdot 10^{-5} \text{ m}^3/\text{s} = 2.543 \text{ l/min}\) representing the total flow through bearing 1.

And \(pr_1 = 1.349 \cdot 10^6 \text{ Pa}\).

From this value it can be seen that due to variations that were implemented to make the bearing easier to manufacture the nominal pressure in a chamber, \(pr\), is not \(ps/2\) but less, leading to a lower stiffness of the bearing.

The total land area of the bearing in \(m^2\) is:

\[
A_{wl} = B_1 \cdot \pi \cdot D_1 - \pi \left( \frac{\pi \cdot D_1}{n} - l_1 \right) \left( B_1 - l_1 - \delta_1 \cdot l_1 - \xi_1 \cdot l_1 \right)
\]

The surface speed of bearing 1:

\[
v_1 = \pi \cdot D_1 \cdot \frac{\text{rpm}}{60} = 9.425
\]

For the friction force in \([\text{N}]\) and moment in \([\text{Nm}]\) in the bearing can be written:

\[
F_{wl} = A_{wl} \cdot \frac{v_1}{ho} \cdot \eta = 0.805
\]

\[
M_{wl} = F_{wl} \cdot 0.5 \cdot D_1 = 0.012
\]

**Radial bearing 2**

In the same way as for bearing 1, the following holds for radial bearing 2:

Given:

- \(B_2 = 20 \cdot 10^{-3}\) [m]  
  Width of radial bearing 2
- \(D_2 = 34 \cdot 10^{-3}\)  
  \(\delta_2 = \delta_1\)
- \(l_2 = l_1\)  
  \(\xi_2 = \xi_1\)
- \(l_2 = 5.9 \cdot 10^{-3}\)  
  \(\zeta_2 = \zeta_1\)

Resulting in:

- \(B_{eff_2} = 0.018 \text{ m}\)
- \(K_{rad_2} = 1.54 \cdot 10^8 \text{ N/m}\)
- \(v_2 = 10.681 \text{ m/s}\)
- \(Q_2 = 4.803 \cdot 10^{-5} \text{ m}^3/\text{s} = 2.882 \text{ l/min}\)
- \(F_{w_2} = 0.842 \text{ N}\)
pr2 = 1.349·10⁶ Pa \hspace{1cm} Mw2 = 0.014 Nm

**Total radial bearings**

Combining the two bearings leads to:

\[ Q_{\text{rad,tot}} = 5.425 \, \text{l/min} \]
\[ M_{\text{wrad,tot}} = 0.026 \, \text{Nm} \]
\[ K_{\text{rad,tot}} = K_{\text{rad1}} + K_{\text{rad2}} = 3.383 \cdot 10^8 \]

The stiffness calculated here is only valid if the load is applied between the bearings. However the load is applied outside the bearing. Therefore the effective stiffness at the point of the load has to be evaluated. For this the axis is first considered infinitely stiff.

\[ \text{L}_{\text{tot}} = 60 \cdot 10^{-3} \, \text{m} \quad \text{Dimension outside bearing 1 to outside bearing 2} \]
\[ \text{L}_{\text{arm}} = 13.5 \cdot 10^{-3} \, \text{m} \quad \text{Distance from outside bearing to load.} \]

The centers of the bearing pockets are regarded as the effective location of the bearings.

Pocket width:

\[ L_{p1} = B1 - l1 - l1 - \delta1 \cdot l1 = 0.018 \quad \text{(A-20)} \]
\[ L_{p2} = B2 - l2 - l2 - \delta2 \cdot l2 = 0.0078 \quad \text{(A-21)} \]

\[ A_{2} \text{ is the distance between the effective locations of the bearings, } A_{1} \text{ from the effective location of bearing 1 to the applied load (see Figure 12):} \]

![Figure 12: Configuration of radial bearings and load](image)

\[ A_{2} = L_{\text{tot}} - (l_1 + 0.5 \cdot L_{p1}) - (l_2 + 0.5 \cdot L_{p2}) = 0.043 \quad \text{(A-22)} \]
\[ A_{1} = L_{\text{arm}} + l_1 + 0.5 \cdot L_{p1} = 0.024 \quad \text{(A-23)} \]

Now the effective radial stiffness at the point of contact of the form roll can be calculated as:

\[ K_{\text{tot,arm}} = \frac{A_{2}^2 \cdot K_{\text{rad2}} - K_{\text{rad1}}}{A_{1}^2 \cdot K_{\text{rad1}} + (A_{1} + A_{2}) \cdot K_{\text{rad2}}} = 6.512 \cdot 10^7 \quad \text{(A-24)} \]

N/m, which is considerably lower that the values for the single bearings mentioned before.
Axial bearing design

The surface that generates the pre-load for the axial (or thrust-) bearing, caused by the difference in diameters of the radial bearings:

\[ A_{\text{pre}} = \frac{\pi}{4} \left( D_2^2 - D_1^2 \right) = 2.01 \cdot 10^{-4} \]  

(A-25)

The bearing consists of two concentric lands because the axis has to extend past the axial bearing. This is indicated in Figure 13.

![Figure 13: Axial bearing dimensions](image)

Take the smallest diameter of the inner land as constraint and determine from this the other land dimensions:

\[ D_{a1} = 17 \cdot 10^{-3} \text{ Constraint by design} \]

Based on a force balance and determined by optimal stiffness demand as \( p_r = p_s/2 \) it follows:

\[ A_{\text{eff ax}} \cdot A_{\text{pre}} = \]  

(A-26)

For the width of the lands a value has to be chosen:

\[ l_d = 2 \cdot 10^{-3} \text{ m} \]

\[ A_{\text{eff ax}} \cdot a = 0.25 \cdot \pi \cdot \left[ (D_{a4} - l_d)^2 - (D_{a4} + l_d)^2 \right] \]  

(A-27)

Solving for \( D_{a4} \) leads to:

\[ D_{a4} = 0.032 \cdot 10^{-3} \text{ m} \text{ leading to } D_{a2} = 0.021 \cdot 10^{-3} \text{ m and } D_{a3} = 0.028 \cdot 10^{-3} \text{ m.} \]
Determine the flow through the bearing:

\[ Q_{ax} = (Cf_1 + Cf_2) \frac{ho \cdot 0.5 \cdot (ps - pa)}{\eta} \]  

(A-28)

In which Cf1 and Cf2 are the correction factors for flow through a circular land [Bee04] defined by:

\[ Cf_1 = \frac{\pi}{12} \frac{1 + \frac{Da_1}{Da_4}}{1 - \frac{Da_1}{Da_2}} \]  

(A-29)

\[ Cf_2 = \frac{\pi}{12} \frac{1 + \frac{Da_3}{Da_4}}{1 - \frac{Da_3}{Da_4}} \]  

(A-30)

Leading to the flow through the axial bearing:

\[ Q_{ax} = 8.897 \cdot 10^{-5} \text{ m}^3/\text{s} = 5.34 \text{ l/min} \]

Next a restrictor has to be dimensioned that will create a pressure drop to 0.5·ps for the given flow.

The type of restrictor is a cylindrical gap restrictor. Diameter and length of restrictor are determined by the designer based on available space, leaving the gap height as a variable.

\[ D_{rest} = 6 \cdot 10^{-3} \text{ m} \quad \text{Diameter of cylindrical gap restrictor} \]

\[ l_{rest} = 16 \cdot 10^{-3} \text{ m} \quad \text{Length of cylindrical gap restrictor} \]

Based on continuity the flow through the bearing and restrictor is equal:

\[ Q_{rest} = Q_{ax} \]  

(A-31)

For the flow through the restrictor:

\[ Q_{rest} = 0.5 \cdot \frac{ps \cdot \pi \cdot D_{rest} \cdot h_{rest}^3}{12 \cdot \eta \cdot l_{rest}} \]  

(A-32)

Leading to a gap height for the restrictor of:

\[ h_{rest} = 8.03 \cdot 10^{-3} \text{ m} \]

The force in [N] generated by the bearing is:

Considering \( pr = 0.5 \cdot ps \)

\[ Fax = 0.25 \cdot \pi \cdot (Da_3^2 - Da_2^2) \cdot pr + 0.25 \cdot \pi \cdot (Da_4^2 - Da_3^2) + \left[ 0.25 \cdot \pi \cdot (Da_4^2 - Da_2^2) \cdot 0.5 \cdot (pr - pa) \right] = 703 \]

(A-33)

The stiffness of the bearing can be evaluated by considering a small variation of the gap width:

\[ \Delta h_{ax} = 0.1 \cdot 10^{-6} \text{ [m]} \quad \text{Axial gap width change.} \]

Resulting in a new gap width:
\[ h_{\text{load}} = h_0 + \Delta h_{\text{ax}} = 1.99 \times 10^5 \]

\[ Q_{\text{ax, load}} = Q_{\text{rest, load}} \]

\[ Q_{\text{ax, load}} = \frac{(C_f' + C_y') h_{\text{load}}}{\eta} (p_r - p_a) \]  

\[ Q_{\text{rest, load}} = \frac{(p_s - p_r) \cdot \pi \cdot D_{\text{rest}} \cdot h_{\text{rest}}}{12 \cdot \eta \cdot D_{\text{rest}}} \]

Solving for \( p_r \) results in:

\[ p_r = 1.763 \times 10^6 \, \text{[Pa]} \]

Which leads to the bearing axial force:

\[ F_{\text{ax, load}} = 709 \, \text{N} \]

The change in force \( \Delta F \) due to the displacement \( \Delta h_{\text{ax}} \) is therefore:

\[ \Delta F = -5.219 \, \text{N} \]

Therefore the stiffness of the bearing in \([\text{N/m}]\) can be calculated as:

\[ K_{\text{ax}} = \frac{\Delta F}{\Delta h_{\text{ax}}} = 5.291 \times 10^7 \]  

The maximum bearing load of the bearing in \([\text{N}]\) is:

\[ F_{\text{ax, max}} = 0.25 \cdot \pi \cdot (p_s - p_a) \left[ (D_{\alpha}^3 - D_{\alpha}^2) + 0.5 \cdot (D_{\alpha}^4 - D_{\alpha}^3) + 0.5 \cdot (D_{\alpha}^2 - D_{\alpha}^2) \right] = 1.41 \times 10^7 \]  

(A-38)

For the friction of the axial bearing:

Land area of axial bearing:

\[ A_{\text{land, ax}} = 0.25 \cdot \pi \cdot (D_{\alpha}^4 - D_{\alpha}^3 + D_{\alpha}^2) = 3.05 \times 10^{-4} \]  

(A-39)

Average surface speed of axial bearing:

\[ v_{\text{ax, av}} = \pi \cdot \frac{D_{\alpha} + D_{\alpha1}}{2} \cdot \text{rpm} \cdot \frac{60}{60} = 7.63 \]  

(A-40)

\[ F_{w, \text{ax}} = A_{\text{land, ax}} \cdot \frac{v_{\text{ax, av}}}{h_0} \cdot \eta = 0.116 \]  

(A-41)

\[ M_{w, \text{ax}} = F_{w, \text{ax}} \cdot 0.5 \cdot \frac{D_{\alpha} + D_{\alpha1}}{2} = 1.41 \times 10^{-3} \]  

(A-42)
**Total bearing**

The total friction of the complete hydrostatic bearing in [Nm] then becomes (at 6000 rpm):

\[ M_{w, tot} = M_{w, ax} + M_{w, rad, tot} = 0.028 \]  \hfill (A-43)

The total flow through the bearing (at ps=3.5 MPa) in [l/min] is:

\[ Q_{tot} = Q_{ax} + Q_{rad, tot} = 10.8 \]  \hfill (10-44)
Appendix B: Normal crushing forces

The crushing forces measured showed rather large variations. For clarity a (running average) smoothened variant of the force data is used in chapter 9, Figure 9-4. Below the original data is shown.

![Crushing Normal Forces for Various Grinding Wheels](image)

*Figure 14: Crushing normal forces for various grinding wheels*

All grinding wheels occasionally show a very sharp rise or fall in forces. This is due to the fact that the dressing passes have been performed in subsets of 25 or 50 passes. When starting with a new subset thermal drift of the machine causes a variation in the effective depth of cut in crushing, \(d_{eff}\), in the first pass of that subset, resulting in force variations. It takes several passes before the process has settled again.

Also in Figure 9-11 filtered force data was shown. The original data of this experiment is shown in Figure 15.
Crushing normal forces for varying crushing depth

Figure 15: Crushing normal forces for varying crushing depth
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He started studying mechanical engineering at the Delft University of Technology in 1996. In June 2003 he graduated cum laude under the supervision of Prof. Dr.-Ing habil. B. Karpuschewski at the laboratory for Precision Manufacturing and Assembly. The subject of this M.Sc. thesis was the modal analysis of a milling machine tool.

During his master studies in 2000 and 2001 he was part-time employed by Komplot Mechanics located in Rotterdam, The Netherlands, and was involved in the development and realization of prototype machine tools.

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