Opportunities for low defect strip welding

*MSc Thesis*

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Abstract

In this research project the feasibility was studied of finding an appropriate way of welding rings for a continuous variable transmission push-belt made out of strip material (~10 mm wide, 0.4 mm thick). The focus was on having the desired dimensions after welding in combination with the desired metallurgical and mechanical properties. The wider aim of this project was twofold; firstly to obtain a higher quality in terms of a smoother surface of the rings, and secondly to reduce the costs of the production of the rings.

The way of achieving these aims was by finding an appropriate welding process that could satisfy the geometrical and metallurgical demands set to the rings for the transmission push-belt. After a literature research different welding processes were tested including laser beam welding, electron beam welding, plasma arc welding, upset welding, flash welding and ‘mash resistance’ welding. Some of these were tested with different experimental arrangements. These experiments were evaluated using optical microscopy, white light interferometry and hardness tests.

The experiments were done on three different maraging steels the trade names which are Ultrafort, Durimphry and Phytime. The Ultrafort did not show similar behaviour to Durimphry and Phytime. This material proved to be less appropriate for this study, whereas Durimphry and Phytime are applicable for the transmission push-belt. The latter two materials did not show metallurgical difficulties during welding.

From these tests four welding processes were found to be applicable for the ring welding of a transmission push-belt. The first two processes are continuous wave laser beam welding and plasma arc welding using two different experimental welding arrangements; a run-on and run-off tab at the start and end of the seam and the second arrangement involved welding different rings adjacent to each other (so called multiple ring welding). The last two processes applicable are upset welding and flash butt welding.
Samenvatting

In dit onderzoeksproject was de haalbaarheid onderzocht voor het lassen van ringen uit lint materiaal (~10 mm breed en 0.4 mm dik), voor de toepassing van een duwband uit een continu variabele versnellingsbak. Hierbij werd de nadruk gelegd op de juiste geometrie van de las in combinatie met de vereiste metallurgische en mechanische eigenschappen. Het hogere doel van deze studie was tweeledig, ten eerste om een hogere kwaliteit van de ringen te bereiken door een gladder oppervlak van de ringen en ten tweede om de kosten van het productie proces te verlagen.

Na een literatuurstudie zijn verschillende lasprocessen getest waaronder laser lassen, electronenbundel lassen, plasma lassen, stiuk lassen, afbrandstuiklassen en een soort van rol naad lassen. Sommige van deze verschillende lasprocessen zijn met verschillende experimentele opstellingen uitgevoerd. De werktuiken zijn geevalueerd met behulp van optische microscopie, wit licht interferometrie en hardheidstesten.

De experimenten zijn uitgevoerd met drie verschillende maraging stalen, de handelsnamen zijn Ultrafort, Durimphy en Phytime. Ultrafort bleek tijdens het lassen een ander gedrag te vertonen dan Durimphy en Phytime. Hierdoor is dit materiaal als minder geschikt gebleken voor dit project, aangezien Durimphy en Phytime wel geschikt zijn voor de toepassing van een duwband. Geen metallurgische problemen zijn gedurende het lassen ontdekt.

Uit de experimenten bleek verder dat vier lasprocessen geschikt waren voor het ring lassen van een duwband. De eerste twee processen zijn continu laser lassen en plasma lassen, beide in combinatie met twee verschillende opstellingen: met een begin en een eind plaatje van maraging staal en de tweede opstelling betrof verschillende ringen direct naast elkaar geplaatst en deze vervolgens aan elkaar te lassen. De andere twee geschikte lasprocessen waren stuiklassen en afbrandstuiklassen.
1. Introduction

This thesis is the final part of the master study in Material Science and Engineering at Delft University of Technology. The project was performed in close cooperation with Van Doorne's Transmissie (VDT, part of the Bosch group) in Tilburg. The project was performed partly at the corporate research laboratories of Bosch in Schwieberdingen (Germany), partly at VDT in Tilburg (the Netherlands) and partly at the TU Delft (the Netherlands).

In this research project the feasibility was studied of directly welding rings for a transmission push-belt out of strip material (~10 mm wide) instead of tubes of sheet (~550 mm wide). The focus was on having the desired dimensions after welding in combination with the desired metallurgical and mechanical properties.

The wider aim of this project was twofold, firstly to obtain a higher quality in terms of a smoother surface of the rings in a transmission push-belt and secondly to reduce the costs of the production of the rings.

The introduction will consist out of three parts, firstly a general introduction of the continuous variable transmission from Van Doorne's Transmissie. Secondly the welding metallurgy of maraging steels is described. Lastly a part on the possibilities for welding strips with the desired geometrical and metallurgical properties. In this part different welding processes are discussed together with the forces acting on the weld zone during welding, causing a certain geometry of the weld pool.

1.1. The (van Doorne) Continuous Variable Transmission

To accelerate a car there are different possibilities. The two most obvious are to have the engine make more rotations in time, or to have the rotational momentum produced by the engine transferred with a different ratio to the wheels. Both, quite simple, ideas are used in every car. To transfer the rotational movement produced by the engine to the wheels different concepts are possible: a stepwise transmission or a continuous variable transmission. The first uses in general fixed gear wheels to change the ratio of the engine to the wheel rotations. The second in the case of the VDT transmission uses a push-belt that runs between two sets of pulleys; the combination is the so called variator, see figures 1 and 2.
Figure 1: Continuous Variable Transmission (CVT) variator consisting of two axis with two sets of conical shaped pulleys and a push-belt.

Figure 2: Schematic overview of the belt, this consists of two sets of 9 or 12 rings connected with elements forming together the push-belt, the push-belt runs between two pulleys.

In the variator torque (or power) is transmitted from the primary to the secondary pulley via friction between the push-belt elements and the pulley sheaves. In figure 3 it is shown that this system can steplessly shift between extremely LOW (underdrive) and OD (overdrive) ratios by varying the pulley clamping forces and thereby changing the axial position of the moveable pulley sheaves. In this way the effective running radius is changed.

The push-belt comprises two sets of 9 to 12 rings and elements connecting the sets of rings together. The elements (see figure 4) push the belt around, and transfer the rotational motion to the second axis. The push-belt is designed for the lifetime of a car, in this lifetime the belt should make about $8 \times 10^7$ rotations. This means that the weld within the ring will bend $1.6 \times 10^8$ times. The push-belt rings are mainly subjected to bending and tensile stresses, in general the bending stresses are determined by the applied running radii and the ring thickness. The tensile stresses are mainly determined by the applied pulley clamping forces, rotational speeds and torque levels. Fatigue will therefore be the reason of failure for a push-belt.
The current method of production

The rings of a push-belt are produced in different steps, these are briefly described below. In the current process a sheet is cut and formed into a tube. These tubes are cleaned, welded with microplasma arc welding, annealed and slit into rings. The rings are deburred with a tumbling process and washed afterwards. Then the rings are stretched by rolling to approximately 97% of their final length and annealed for a second time. The final calibration process follows where the rings at this stage are stretched to their final length. They are then hardened, oxidized and nitrided the final step is the sorting by actual length for an ideal set of nine or twelve rings fitted over each other. The sets of rings are then put together with the friction elements. These are produced by stamping, washing, hardening, deburring, controlling and assembling with the rings forming a transmission push-belt.

The new method of production

The challenge to improve the quality of the push-belt will be to improve the surface quality of the material. Three different types of maraging steel have been examined; Ultrafort, Durimphy and Phytime. Within the Durimphy maraging steel, the main weaknesses are TiN and TiC precipitates; these are often found as initiators for fatigue cracks. For the Phytime maraging steel, a material without titanium, the surface defects are the next critical initiator for fatigue cracks. For further improvement there may be an opportunity to weld high surface quality strips to form the rings, and these could be directly rolled. With this process, the steps from decoiling until the cleaning of the rings can be replaced as shown in figure 5. For the ring welding method the strip material should be decoiled, cut, formed, washed, welded, post-treated and annealed. It is then ready for further rolling. The major profit in quality and costs can be reached in skipping the tumbling process.
1.2. Welding maraging steel

The rings are produced from maraging steel, this material is chosen because of its high strength and high toughness properties. Maraging steels are a group of mainly iron-nickel alloys that are martensitic (MAR-), and are strengthened by precipitation hardening (AGING) of mostly intermetallic compounds. The matrix contains no significant amounts of carbon, preferably ranging from 0 – 0.03 wt%. Other elements that are commonly used in maraging steels are Co, Mo, Ti, Cr and sometimes Al, V, W and Mn [1, 2].

In the early sixties maraging steel was developed starting from compositions of 18 wt% Ni and between 20 and 25 wt% Ni in combination with 6-16 wt% Co. Cobalt was added to improve the toughness of the material and make it less brittle, in combination with molybdenum the alloy showed a much better hardening. The 20 wt% [3] and 25 wt% alloys are less used because these need to be cooled to sub-freezing temperatures to form the martensite [4].

The phases that are present in the Fe-Ni binary alloys are shown in the Fe-Ni diagram in figure 6 [3]. This shows the transformation temperature of austenite to ferrite and the stable phases of nickel and iron.
Figure 6: Fe-Ni Phase diagram, for 18% Ni it shows stable α-Fe and FeNi₃ [3].

As the phase diagrams show the equilibrium phases only and not metastable phases such as martensite, figure 7 [5] is needed to describe the martensite phase transformation in Ni-Fe alloys. This figure shows the transformation temperatures on heating and on cooling. The transformation from austenite to martensite is found to be independent of the cooling rate and therefore characterized as a diffusionless transformation.

Figure 7: Start and stop temperatures from austenite to martensite transformation [5].

To conserve ductility within the martensitic structure the carbon content should be as low as possible. To achieve this in many maraging steels titanium is
added which binds the residual carbon. A disadvantage of the addition of titanium is the formation of TiN and TiC particles. As indicated before, these can initiate fatigue cracks. With low carbon content a lath type martensite will be formed. This type is characterized by a high density of dislocations and an absence of transformation twins. The difference between iron-nickel martensite and iron-carbon martensite is that the latter has a certain degree of body-centered tetragonal structure (BCT) that is proportional to the concentration of carbon. In the BCT structure the carbon occupies an interstitial site [6]. The iron-nickel martensite has a BCC structure [4], the absence of interstitial carbon is positive for the toughness of the material.

When maraging steels are heated over 1000 °C three different types of reactions take place in the austenite during cooling. The first reaction is a grain boundary embrittlement reaction due to segregation of M(C, N), these precipitate in thin films on the grain boundaries and cover a significant fraction of the grain boundaries (the metal M is primarily Ti). A second reaction is the formation of ageing products in the austenitic phase, these are intermetallics such as Fe₂(Mo, Ti) and Ni₃(Mo, Ti). The third reaction is the reaction from austenite to martensite [2]. These reactions are shown in figure 8.

![Figure 8: Precipitate formation in maraging steel depending on temperature, time and composition [2].](image)

In the martensite, different reactions can take place, such as hardening by forming Ti(C,N) particles. Other precipitates for hardening are formed by the combination of cobalt and molybdenum where the cobalt lowers the solubility of the molybdenum and therefore increases the amount of molybdenum-rich precipitates such as Ni₃Mo and Fe₂Mo [2, 7, 8]. Next to this effect, the cobalt strengthens the material due to the short range ordering reaction in the matrix and it also increases the martensite start temperature (Ms). Besides these reactions many other strengthening reactions can take place depending on the composition of the base material [7, 9, 10].
The effect of different ageing temperatures and times on the hardness is shown in figure 9 [2]. This shows the ageing behaviour on the long term. During the ageing process diffusion takes place and different intermetallic precipitates are formed, mainly Ni$_3$Mo and Fe$_3$Mo. An initial hardening reaction is not shown within this figure. In different studies it has been shown that welding in an aged state reduces the quality in terms of strength significantly. Better results are achieved when welding and then afterwards applying an ageing process [11, 12].

![Figure 9: Hardening behaviour from maraging steel with an optimum shown for the ageing temperatures and times [2].](image)

To give a general indication of the physical properties of maraging steel table 1 is included and table 2 shows an overview of the influence of the different elements on the maraging steel.

**Table 1: Physical properties for an 18% maraging steel**

<table>
<thead>
<tr>
<th>Property</th>
<th>Maraging Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m$^3$)</td>
<td>8.0*10$^3$</td>
</tr>
<tr>
<td>Coefficient of thermal expansion (µm/K m)</td>
<td>10.1</td>
</tr>
<tr>
<td>Thermal conductivity (at 20°C) (W/K m)</td>
<td>19.7</td>
</tr>
<tr>
<td>Electrical resistivity (at 20°C) (µΩ m)</td>
<td>0.44</td>
</tr>
<tr>
<td>Melting temperature (°C)</td>
<td>1430-1450</td>
</tr>
<tr>
<td>Curie point (°C)</td>
<td>330-350</td>
</tr>
</tbody>
</table>
Table 2: Overview of the general influence of the different elements in maraging steel

<table>
<thead>
<tr>
<th>Element</th>
<th>Content [wt%]</th>
<th>Influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>Bal.</td>
<td>Relative cheap element for high strength application</td>
</tr>
</tbody>
</table>
| Ni      | 18-20         | - Austenite formation  
- Formation of Ni$_3$Mo particles  
- If concentration < 20% Ni lath type of martensite  
- If concentration > 20% Ni twinned martensite [13] |
| Co      | 6-17          | - Enhance the formation of Mo precipitates during ageing  
- Austenite formation  
- Increases the martensite start temperature |
| Mo      | 4.5-5.5       | - Formation of ferrite  
- Formation of precipitates Ni$_3$Mo, Fe$_2$Mo and Fe$_7$Mo$_6$ |
| Ti      | 0-1.5         | - Formation of TiC and TiN particle, this supports the toughness of the material, and improves the strength after ageing  
- Formation of Ni$_3$Ti precipitates |
| C       | 0-0.03        | - Low for good toughness properties |
| Cr      |               | - Cheap substitute for Co, although the high quality of Co containing maraging steels cannot be achieved |
| Al      | 0-0.15        | - Extra clustering effects during ageing |

During fusion welding of maraging steel the material is heated above the melting point. In the material next to the weld pool an increase in the temperature is achieved by thermal conductivity of heat from the weld pool. The maximum temperature that is reached in the material decreases with distance from the weld pool. As a result the material undergoes phase transformations during heating and cooling see figure 6 above.

![Figure 10: Microstructure from plasma joint, A is the fusion zone, B is the coarse grained martensite zone, C light etched zone, D the dark etched zone and E the base metal.](image)

A typical weld is shown in figure 10. In the heat-affected zone (HAZ) three different microstructures can be recognized, first a coarse grained zone (B) with martensite next to the weld pool (A), second a light etching region (C) with martensite and third a dark etching region (D) with martensitic grains and on the grain boundaries a thin layer of austenite can be present. Some papers also report the presence of austenite in the fusion zone [14]. In these zones, the dark etched zone
and the fusion zone, a diffusion-controlled decomposition of martensite takes place according to equation 1

\[
\alpha \rightarrow \alpha' + \gamma'
\]

Where \(\alpha\) is the martensitic phase and \(\alpha'\) is the alloy depleted martensite, and \(\gamma'\) is the alloy-rich stable lath-like austenite. The peak temperatures reached in the dark etched zone are in the range of 590°C – 730°C [10]. In the dark etched zone some hardening products are formed [14]. With multi-pass welding more segregation of Ti and Ni will occur. With microhardness tests the hardness of the austenite and the martensite can be tested and with energy dispersive X-ray analysis (EDAX) or with an X-ray diffraction microscope local composition analysis have been performed [14, 15]. The amount of nickel and alloying elements in the austenite phase differs significantly from the depleted martensite. Some of these values are given in table 3 [16] for the different locations in a weld and the heat affected zone.

**Table 3: Alloy compositions of the different regions in the joint, titanium concentration is increased significantly in the austenite phase.**

<table>
<thead>
<tr>
<th>Analytic site</th>
<th>Content of alloy wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ni</td>
</tr>
<tr>
<td>Base metal (E)</td>
<td>18.05</td>
</tr>
<tr>
<td>Light etching region (C)</td>
<td>16</td>
</tr>
<tr>
<td>Dark-etching region (D)</td>
<td>17</td>
</tr>
<tr>
<td>Austenite Phase</td>
<td>17</td>
</tr>
</tbody>
</table>

**Figure 11: Maraging steel in an aged condition (3h 520°C) with austenite pools on the grain boundaries, etched with Fry’s reagent [10].**

The best results are achieved when the heat input is as low as possible. This limits the segregation and austenite formation in the dark etched zone to a minimum.
The formation of austenite is shown in an isothermal transformation diagram, figure 12 [14]. From this diagram the transformation is expected at a temperature of 371°C (700°F) to start after 29 to 36 seconds. From figure 13 the formation is expected in an earlier stage, from a heating rate of 222 °C/s (400 °F/s) [4]. Some studies with welding maraging steel have been done in the aged state, where to reach the required properties a re-ageing treatment must be carried out since all the hardening products are dissolved during welding and the material at the location of the weld has an unaged state.

Figure 12: TTT-diagram for the formation of austenite within an 18% Ni maraging steel [14].

Figure 13: Phase and precipitate formation for different heating rates
1.3. The Challenges

The initial tests gave a good indication for the challenges that would be faced for this project. These tests were done with laser welding in a butt weld configuration; the results can be transferred to other fusion welding processes. The weld pool showed irregularities at the start and at the end of the seam. The end of the seam contracted and a defect appeared with a typical size of about 150 µm see figure 14. One challenge in welding will be to reduce this defect to a size of 5-15 µm and an absolute maximum of 50 µm.

![Welding direction](image)

Defect depth of 150 µm

Defect width of 300 µm

200 µm

Figure 14: The end of the seam on a strip, also called run-off shows a large defect of about 150 µm deep and 300 µm wide for this sample.

The weld quality will need to be the same quality as that of the current process. To measure the quality, the geometrical surface dimensions are the obvious targets as these act as stress concentrators and crack initiators during continuous loading. The edges of the ring (the ‘facet’) can have a maximum defect of 50 µm at this production stage (the shape of this defect is not defined). The welded rings will need to compete with the rings after tumbling, the tumbling process levels height differences in the surface of the material (for example in the weld bead). The surface geometry of the seam after plasma arc welding is shown in figure 15.

The amount of deformation near the weld due to rolling is not easy to predict. With the current process there is a significant deformation near the weld pool, the maximum height difference at the surface is 31 µm before rolling and tumbling and after rolling (without tumbling) 1 µm. The difference in the surface geometry due to tumbling is that the seam cannot be distinguished by the height profile, smooth height differences in the order of 1 µm are still present in the ring material. The rolling will level the surface geometry and the amount of this levelling that is possible is not clear at this stage.
Figure 15: Height profile of a plasma arc welded seam after welding, the plasma weld shows a decrease in height in the middle of the seam.

1.3.1. Possible welding methods

A literature survey [15] showed different welding processes which are applicable for the welding of strip material for rings of a push-belt. These are plasma arc welding, laser beam welding, electron beam welding, and resistance welding processes like pressure upset welding and flash butt welding. These processes are briefly described below.

Plasma arc welding

Plasma arc welding (PAW) can be compared to gas tungsten arc welding (GTAW), because both make use of a non-consumable tungsten electrode and are covered by a shielding gas. Both processes are shown in figure 16. There are different advantages to plasma arc welding over gas tungsten arc welding. Firstly the more concentrated heat input of PAW due to the constricted arc. This has two consequences, higher welding speeds are possible or a lower current can be used, which lowers the heat input. A second benefit is a more stable arc and the arc has a greater directional stability. A third advantage is the possibility for a narrower bead. A special variant of PAW is microplasma welding this process can deliver low current in a stable manner and is therefore very suitable for welding thin sheet (0.1 mm to 0.5 mm) [16].
Figure 16: Left a plasma torch, small plasma gas orifice and a cover gas supply, right a GTAW torch with one wide shielding gas supply [16].

For plasma arc welding the torch consists of two gas flow chambers, and an electrode. The first gas used is a plasma gas (also called orifice gas) often an inert gas such as argon. This plasma gas is used with a flow rate of about 0.25 to 5 l/min. The plasma gas flows through a small orifice and this will result in a high flow speed. It is this gas that can exert a pressure on the weld pool to create a keyhole. The keyhole makes deep penetration welding possible.

The plasma gas is not sufficient to prevent oxidation. For the prevention of oxidation a secondary gas, the shielding (auxiliary) gas such as Ar/H₂ Ar/He or Ar is necessary, the additions of hydrogen or helium to the argon gas gives higher arc energies. The flow of the auxiliary gas is in the order of 10 to 30 l/min [16].

The electrode is made out of tungsten, and is recessed within the water cooled copper nozzle. For direct current electrode negative (DCEN) the tungsten electrodes usually have additions of elements such as thoria, zirconia or ceria. The shape of the electrode is conical with a tip angle between 20 and 60 degrees for direct current electrode negative. For square wave alternating current the electrodes are balled or flat to prevent the electrode from overheating and to maximize the current capacity. The shape of the weld pool from a DCEN arc has a greater depth to width ratio, developed by the electromagnetic forces, in comparison with direct current electrode positive. An overview of the setup is given in figure 17. A filler material can be used and can be fed by an external supply.
A classification of the different plasma welding processes used is based on the current [17]. For microplasma this is about 0.05 to 15 A (thin sheets from 0.1 mm), for medium current 15 to 200 A, and for keyhole plasma currents over 100 A are typically used (strips with thickness of over 2.5 mm). These are quite general indications of the different plasma welding classifications. For keyhole welding the actual keyhole is not created by the current flow but by the pressure of the orifice gas on the weld pool. Since microplasma welding would be the most suited process for this application this is further discussed below.

The three kinds of arcs used in microplasma welding are transferred arc, non-transferred arc and a semi-transferred arc. With a transferred arc, the current flows from the workpiece to the tungsten electrode. For a non-transferred arc the current flows from the plasma gas nozzle to the tungsten electrode. The latter is mainly used for metal-spraying and for welding of metal foil strips. The semi-transferred arc is a combination of these two methods.

With regard to polarity there are three possibilities; an alternating current, a direct current with the electrode positive and a direct current with the electrode negative. The latter is most often used in applications. With direct current electrode positive the applications are limited to aluminium welding. The disadvantage in this welding method is the excessive heating of the electrode and the limited current capacity.

**Laser beam welding**

At the present time lasers are widely applied in material treatment, for instance in cutting, hardening, drilling and welding. With lasers it is possible to deliver concentrated energy to the material. The energy in the form of photons is transformed into heat when the electromagnetic waves are adsorbed by the metal.
Depending on the energy density of the beam the material can melt or evaporate. The local melting of the material can be used to cut or to join metals. The main interest in this study is to use it as a welding tool.

The energy input from the laser into the material is dependant on several factors. These are the adsorptivity of photons by the metal, thermal conductivity, heat capacity, laser intensity, pulse shape, beam polarization, fluctuations of laser output, plasma interferences, dynamic instabilities in the liquid and vapour flow during welding. All of these factors make laser welding a complex subject for analysis.

The energy balance for laser welding is shown in equation 2 and visualized in figure 18 for the different welding modes [18].

\[ P_L = P_{\text{refl}} + P_{\text{abs}} + P_{\text{trans}} + P_{\text{plasma}} + P_{\text{vap}} \]  

(2)

Where \( P_L \): Laser power  
\( P_{\text{refl}} \): Reflected laser power  
\( P_{\text{abs}} \): Adsorbed laser power  
\( P_{\text{trans}} \): Transmitted laser power  
\( P_{\text{plasma}} \): Power shielded by the plasma  
\( P_{\text{vap}} \): Power lost by the evaporation of the metal

![Diagram showing energy balance in laser welding](image)

Figure 18: Laser power applied on a weld pool, conduction mode welding left and keyhole mode welding right [18]

In table 4 the absorptivity of some metals at room temperature are shown. As can be seen the absorption of the laser light by metals is in general quit low. The absorptivity and the refractive index depend on factors such as wavelength, temperature and oxidation layers. The absorptivity of the metal determines the effectiveness of the laser welding process.
Table 4: Absorptivity of different metals at room temperatures, only a small part of the laser power is absorbed and used for melting the material.

<table>
<thead>
<tr>
<th>Material</th>
<th>A for 1.06 μm (Nd:YAG)</th>
<th>A for 10.6 μm (CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>0.06</td>
<td>0.02</td>
</tr>
<tr>
<td>Cu</td>
<td>0.05</td>
<td>0.015</td>
</tr>
<tr>
<td>Fe</td>
<td>0.1</td>
<td>0.03</td>
</tr>
<tr>
<td>Carbon steel</td>
<td>0.09</td>
<td>0.03</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>0.31</td>
<td>0.09</td>
</tr>
</tbody>
</table>

If the intensity of the beam is increased, the welding process has four steps. Firstly the material is heated up to the melting temperature, surface treatments can be given in this way. Secondly the melting temperature is reached; welding in conduction mode is made possible. Thirdly, the vaporization temperature is reached, this induces keyhole welding. Finally the light intensity is so high that the vaporized particles are excited into a plasma.

Two different modes can be distinguished in laser welding, the first is conduction mode welding and the second the keyhole mode. With conduction mode welding a laser beam is used to melt the material, the heat is conducted into the material and the melt advances into the material. The surface of the weld pool remains relative flat during welding.

The keyhole formation starts when the vaporization temperature is reached in the melt pool. The vapour exerts a recoil pressure on the melt pool, and opens up the melt pool. In total five pressures influence the shape of the weld pool; these are the hydrostatic pressure (pₜ), surface tension (pₒ), vapour pressure (pᵥ), recoil pressure (pᵣ) and the radiation pressure (pᵣ) [19]. Where the first two factors tend to restore the melt and the last three tend to open the keyhole. The two factors that are dominant in this process are the surface tension and the vaporization pressure.

The vapour arising from the seam absorbs light and can form a plume or even a plasma above the focus spot. The absorbed light represents energy taken away from the laser power. The formation of the plume is inherent to keyhole welding due to the amount of vaporized particles needed.

There are two modes of laser operation for welding either a continuous wave laser (cw) or a pulsed mode laser (pm). A cw laser has a constant power output and produces thus a continuous seam. Where a pulsed mode laser produces relative short pulses (typical 1-20ms), and a seam is made by an overlap of these pulses. Both methods can produce either a keyhole or a conduction mode, and both are applicable for a butt weld. The main difference is that with a pulsed mode laser the weld pool is not continuous, and this has consequences for the possibilities of material transport.

During fusion welding the material is first transformed into a fluid and afterwards transformed back to a solid. In the period when the material is melted the dynamic behaviour must be taken into account. The same pressures as mentioned with keyhole welding act on the surface, only the vaporization force does not need to
be dominant. Depending on the mode that is used for welding (conduction or keyhole), the flow has different characteristics. Indication for the fluid flow in the seam is given in figure 19.

![Diagram of flow pattern in a conduction mode weld pool](image)

**Figure 19:** Flow pattern in a conduction mode weld pool, the flow is mainly determined by the surface tension gradient [18].

In addition to the Marangoni convection, one other effect is present with conduction welding with a laser, this is the buoyancy convection. The buoyancy forces are based on the difference in density of the melt with different temperatures. This is a relative weak force and is not dominant.

For keyhole welding the shape of the weld pool is significantly different see figure 20 [18]. The keyhole is created by the vaporization pressure. The combination of the vaporization pressure, the surface tension, the heat flow and the welding velocity mainly determine the shape of the weld pool.

![Diagram of keyhole mode weld pool](image)

**Figure 20:** Typical shape of a keyhole mode weld pool, heat and fluid flow in combination with the vaporization pressure and surface tension mainly influence the fluid shape of the weld pool [18].
Electron beam welding

The application of highly accelerated electrons for material processing has been employed for drilling and welding. Most of the electron beam welding machines are built up from three main components; the beam generator, the beam manipulation system and a working chamber. The different components may have separate vacuum systems. The operation of the electron beam welding machine is briefly described in this section.

Figure 21: Schematic overview of the electron flow in the electron gun consisting out of an anode, cathode and a control electrode.

The beam generation component also consists of three main parts, a cathode, an anode with a small hole and a control electrode see figure 21. The combination of these three elements is also called a triode. The cathode is heated to increase the energy of the conduction band electrons; this increase leads to an increase in emission of electrons from the surface of the cathode. A negative voltage is applied to the cathode, and due to the electrical field between the anode and the cathode the electrons are accelerated in the direction of the anode. The amount of acceleration is dependent on the voltage difference between the cathode and the anode, i.e. the electrical field strength. The relationship between accelerating voltage and electron speed is shown in figure 22 [20].
Figure 22: Relation between the acceleration voltage and the electron speed, the nearer the speed of light is approached the less efficiently the electrons are accelerated [20].

The third element of the electron beam welder, the control electrode allows for better control over the beam current. This control electrode has a more negative voltage than the heated cathode; the negative voltage repels the electrons and can therefore control the amount of emission of electrons from the cathode. A schematic figure of the beam flow is shown in figure 21 above [20].

The beam manipulation section also consists of three parts, a focusing lens, a deflection system and a stigmator. A schematic representation of an electron beam welding machine is given in figure 23. The focusing lens is necessary to produce the required power density for welding. The lens is constructed from an annular coil that produces a magnetic field through which the electron beam is fed. With the proper magnetic field, the beam can be focused on the workpiece. The deflection system can bend the electron beam in the required direction. This deflection is also made possible with electromagnetic fields. The non-mechanical way of movement of the energy source is unique for welding. The third component needed for beam manipulation is the stigmator which corrects stigmatic aberrations. It corrects for electrical and magnetic interferences and prevents the formation of an elliptical shape of the beam spot when altering the axial direction and keeps the beam circular.

The working chamber is the third section where the workpieces are positioned. Below the different chambers an orifice is placed that is large enough to
pass the beam but small enough to impede significant back diffusion of volatile elements emanating from the workpiece into the lower pressure chamber.

![Diagram of electron beam welding machine](image)

Figure 23: Schematic representation of an electron beam welding machine [16].

The input of energy to the joint can be controlled with four basic parameters: [16, 21]

- Beam current, the number of electrons, controlled with the heat of the cathode and the voltage on the control electrode.
- The velocity of these electrons, controlled with the voltage over the cathode and the anode.
- The focus of the electron beam on the surface controlled with the electromagnetic lens, the deflection system and the beam correction systems (stigmator).
- Welding speed, depending on the deflection system and a possible handling system.

The characteristics of the welds are different for EB-welding in vacuum and at atmospheric pressure (Non-Vacuum Electron beam welding, NV-EBW). For high vacuum EB-welding processes a highly focussed beam can be achieved with typical diameters for electron welding beams ranging from 0.1 to 1 mm. This has some advantages; firstly sheet thicknesses from 0.1 mm to 300 mm can be welded. Secondly, a power density of $10^7$ W cm$^{-2}$ can be achieved with the advantage that a joint with a high depth-to width ratio can be created. The weld has a low overall heat
input and high welding speeds are possible especially for thick sections. Because the weld is performed under vacuum no shielding gas is required and oxidation does not take place due to the lack of oxygen.

For Non-Vacuum electron beam welding the shape of the beam changes compared to vacuum EBW. This change is due to the interaction of the air and the electrons. The beam diverges rapidly caused by scattering and ionisation. Power density and efficiency rapidly decrease as a result of the interaction with the air, see figure 24 [22]. The advantage of the diverging beam is that the process has a better gap bridging capability. In general accelerating voltages higher than 150 kV are necessary for NV-EBW for welding. In a helium environment it is possible to weld with lower accelerating voltages due to lower interaction between electrons and helium gas. When the beam has sufficient power the local gas pressure decreases due to local heating, this increases the efficiency of the process. The maximum welding thickness for NV-EBW is about 10 mm.

![Figure 24: Electron beam widening for different pressures, with higher pressures less focusing is possible [22.]](image)

Because the direction and focus of the beam is not controlled by mechanical processes but by magnetic focusing devices, it is possible to control the beam in such a way that at the same time different weld pools can be created on different locations. This possibility of discontinuous focus systems is unique for beam welding technologies. When welding with a split beam creating two spots there is the option of pre- or post heating of the material [23], this is a unique feature.

**Resistance welding**

With resistance welding a bond is made between two metals by a combination of pressure and heating the material locally with electrical resistance. Different forms of resistance welding exist; common processes are resistance spot welding, resistance seam welding, upset welding, flash welding, percussion welding, high frequency resistance welding and projection welding. General characteristics of resistance welding processes are the high speed of the process, high reliability, high
joining efficiency and the relative low capital and operating costs [19]. In this chapter the processes interesting for butt welding of thin strips are discussed. Some applications of resistance butt welding are band saws, wire welding, chains and wheel rims.

Heat is a critical parameter in the resistance welding process. The heat generated in an electrical conductor is dependant on three factors; the current, the resistance of the components and the duration of the current this can be shown by equation 6.

\[ Q = \int_{t_{\text{on}}}^{t_{\text{off}}} I^2 \cdot R(T) \cdot dt \]  \hspace{1cm} (6)

Q= heat generated [J]
I= current [A]
R= resistance [Ω]
t= duration [s]
T=temperature [K]

With the generated heat the temperature of the material is increased. The change in temperature can be described with equation 7

\[ \Delta T = \frac{\Delta Q_{\text{local}}}{mC_p} \]  \hspace{1cm} (7)

Cₚ= heat capacity [J kg⁻¹ K⁻¹]
m= mass [kg]

For a resistance welding circuit, heat is generated in the electrical circuit due to the resistance. Two kinds of resistance can be recognized: bulk resistance and contact resistance. The former is a function of temperature, where metals exhibit a positive temperature coefficient. This means that the resistance increases with the temperature. The latter is the resistance between the interfaces and is dominant in the first milliseconds of the welding process. A general development of the resistance during welding is shown in figure 25 [24]. It is important that the highest resistance is located at the interface of the workpieces. At this place most of the heat will be generated. Other places where high resistance is located are the interfaces between the electrodes and the workpieces at the start of the welding process. The characteristics of the different processes are discussed below.
Figure 25: Development of the electrical resistance during resistance welding, \( R_{\text{ges}} = R_{\text{c}} + R_{\text{s}} \), where \( R_{\text{ges}} \) is the total resistance, \( R_{\text{c}} \) is the contact resistance and \( R_{\text{s}} \) is the resistivity of a material [24].

For making a joint, pressure is applied in addition to the current. The direction of the force is normal to the welding surface. This pressure has three different effects, firstly it ensures the electrical contact between the different workpieces, secondly it reduces the contact resistance between the two workpieces due to the improvement of the contact between the surfaces, and finally it ideally presses all the irregularities existing on the surfaces outside of the seam into the flash.

For resistance welding the current supply is important. As was stated in equation 6 the current is the main supplier for heat. For the current supply four different types of power sources are available for resistance welding: stored energy (capacitive discharge), direct energy (AC), high frequency inverter welder (HFDC) and transistor direct current (linear DC). An overview of several possibilities is given in table 5.
Table 5: Overview for the different possibilities for current supply with resistance welding

<table>
<thead>
<tr>
<th>Power supply</th>
<th>Typical current flow [25]</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor power supply</td>
<td><img src="image" alt="Current waveform" /></td>
<td>- Limited controllability of the current flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Limited amount of current flow</td>
</tr>
<tr>
<td>AC power supply</td>
<td><img src="image" alt="Current waveform" /></td>
<td>- Relative inefficient heating</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Cheap process</td>
</tr>
<tr>
<td>High frequency inverter</td>
<td><img src="image" alt="Current waveform" /></td>
<td>- Good controllability over the current</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Relative cheap compared to the transistor DC power supply</td>
</tr>
<tr>
<td>Transistor DC power supply</td>
<td><img src="image" alt="Current waveform" /></td>
<td>- Excellent controllability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Expensive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Lower repetition rate in comparison with a high frequency inverter</td>
</tr>
</tbody>
</table>

**Upset welding**

Upset welding is a resistance process that has as a characteristic that no melting takes place during the welding process. For upset welding different process parameters are available; welding current, force and time. The process can be briefly described as placing the workpieces against each other, applying a current, heating up the interface of the workpieces and applying a pressure simultaneously. Pre-heating and post-heating can be done if desired.

For reproducible results different factors are important, for example joint preparation, precise alignment, and controllability over force and current. For a
proper joint preparation the surfaces should be flat, perpendicular to the upset force and cleaned of dirt, oil, oxidation, etc. The alignment determines the current density and the amount of contact resistance; this has an influence on the heat development. For a constant heat development it is necessary to have a good alignment, furthermore a good alignment improves the strength of the seam. Controllability of the current and the pressure is important for the heat development and the final length of the workpieces [16, 21].

**Flash welding**

Flash welding is a resistance welding process that has some features in common with upset welding. Similarities are the devices needed to produce a weld, a current source for heating based on electrical resistance and a high precision clamping device. The basic difference is that the pressure is only applied after the heating is done and therefore melting occurs with flash welding. The upset force should be much higher with larger welding surfaces in case of upset welding therefore flash welding is typically used when welding surfaces from 50 to 120000 mm² and upset welding typically for smaller surfaces varying from 1 to 600 mm² [24].

With flash welding two stages can be identified, the flashing and the upset stage. The heating of the parts is done by the current flow. During the flashing stage a flashing voltage is applied, the workpieces are moved rapidly away from each other and then brought in contact. During this movement flashing occurs by the minute arcs that are formed and the faying surfaces are heated to a temperature above the melting temperature. During the subsequent upset the workpieces are pressed together with a controlled upset rate, over a controlled distance and with a controlled current to keep the workpieces at the desired temperature level. The upset force needs to be higher than the yield strength of the heated material.

During the upset a flash is created, this is inherent to the process, and this will have to be removed after welding. A major advantage is that the oxides and the molten material will be pushed out of the seam which increases the quality of the seam. For minimizing the contaminations in the fusion zone the welding can be performed under protection of a shielding gas.

**1.3.2. Forces during welding**

During a fusion welding process different forces can act on the surface of a weld pool. The shape of the surface will be influenced by these forces and this will influence the shape of the seam after solidification. Here the combination of controlling the fluid flow with the heat flow comes together. The fluid flow can be driven by forces developed by the surface tension gradient, electromagnetic flow, buoyancy gradient, vapour pressure, recoil pressure and gas flow. These are briefly described in this section. It is important to have an understanding of the different forces acting on the weld pool because these determine the shape of the weld pool.
and fluid flow in the weld pool. These will help in understanding the observed geometries of the solidified weld pool.

**Surface tension**

Surface tension was first seen as a driving force within convection by Marangoni in the nineteenth century and was further explored by Heiple in 1982. The surface tension is the force acting along a unit of length [N/m] and can be described as the work that needs to be done to create from a length of 1 m a surface of 1 m², the surface energy [J/m²] and the surface tension [N/m] are numerically equal. The latter is most often used with fluids and the surface energy with solids [26]. The surface of the weld pool is as small as possible due to the surface tension; this tension is responsible for the contraction of the weld pool at the start and end of a joint.

Next to the contraction of the weld pool at a free surface, the surface tension also causes a fluid flow in the weld pool. The forces appearing on the weld pool are a function of the change of the surface tension with temperature gradient. With most pure metals the surface tension decreases with the temperature. For metals containing surface active elements like sulphur and oxygen this trend can be opposite [27]. For example, the calculated values of surface tension for oxygen in iron are shown in figure 26 [22].

![Figure 26: Calculated values for the surface tension of iron with dissolved oxygen [18], with high oxygen content the surface tension first increases with the temperature.](image)

The convection, driven by the surface tension gradient, is in the direction of the higher surface tension. In case of normal metals this would be the coldest part of the weld, the outside of the weld pool. This is shown in figure 27. With the flow in the weld pool, the penetration is affected as well, with an outward flow the penetration is less compared to an inward flow.
Figure 27: Model for Marangoni convection in a weld pool, a. dependence between surface tension and temperature for low surface active element concentration, b. surface gradient and created flow direction, c. outward flow, d. surface tension vs. temperature for high surface active element concentration, e. surface gradient and created flow direction, f. inward flow [18].

Summarizing the influence of the surface tension, it is twofold, firstly the surface tension can create a flow in the weld pool during welding due to a temperature dependence of the surface tension, and secondly the surface tension is expected to have a significant influence of the formation and closure of the keyhole during welding. The most favourable energy state for the surface tension is the state with the lowest surface area.

For keyhole welding extra surface is created, in the dynamics of the weld pool during keyhole welding the surface tension plays an important part. Within the cylinder of the keyhole the pressure that is created by the surface tension, is working as a closing pressure and can be described with

\[ p_r = \frac{\gamma}{r} \]  \hspace{1cm} (8)

\( \gamma \) = Surface tension [N/m]
\( r \) = Radius of the keyhole [m]

For the bottom of a closed keyhole the pressure created by the surface tension is described with

\[ p_r = \frac{2\gamma}{r} \]  \hspace{1cm} (9)

**Buoyancy**

Within the weld pool, temperature gradients are present, the temperature on the sides of the weld pool are in general lower than in the centre of the weld pool. The density of liquid metal decreases with increasing temperatures this has the consequence that a circulation flow is created, as shown in figure 28. This process is most of the time not the dominant force, but should be taken into account [22].
Figure 28: Direction of the flow created by the buoyancy force, left the location of the force, middle the change of density vs. time, right the flow direction as a consequence of the forces [22].

Gravitational pressure

A third pressure that needs to be considered is the gravitational pressure (hydrostatic pressure) which is within a keyhole related to the density and the height of the liquid material. During keyhole welding this is a pressure exerted on the sides of the keyhole. The pressure increases with the depth of the weld pool and can be responsible for the closure of the keyhole. It is described with equation 10.

$$p_g = \rho gh$$  \hspace{1cm} (10)

$\rho = \text{density [kg/m}^3\text{]}$
$g = \text{gravitational acceleration coefficient [m/s}^2\text{]}$
$h = \text{height [m]}$

Electromagnetic flow

For welding processes with electron transfer the current flows through the workpiece and converges near the surface towards the arc. As this current induces a magnetic field a net downward Lorentz force is created. This force creates a flow initiated in the centre, exerts a downward force to the material and as the liquid metal can only flow within the weld pool it will create an inward flow. This can be described with equation 11 [26].

$$F_L = \rho_e E + J \times B$$  \hspace{1cm} (11)

$F_L = \text{Lorentz force [N]}$
$\rho_e = \text{charge density [C/m}^3\text{]}$
$E = \text{electrostatic field [V/m]}$
$J = \text{current density [A/m}^2\text{]}$
$B = \text{magnetic field [T]}$

The flow of material from the surface to the bottom of the weld pool transfers heat by convection to the lower part of the weld pool. This convection can make the weld pool significantly deeper independent of the direction of the current. The current density in the weld pool, the Lorentz force that is induced and the fluid flow within the weld pool is simulated by Tsai and Kou. The result is shown in figure 29. This is a
dominant force within arc welding processes, for electron beam welding processes currents are a factor 100 lower than for arc welding processes, this makes the electromagnetic force small.

Figure 29: Simulation of convection in a weld pool for aluminium, a. fluid flow field, b. current density field, c. resulting Lorentz force field [22].

Vapour pressure

With keyhole welding a vapour pressure is present in the keyhole. When the temperature of the weld pool exceeds the vaporization temperature, the metal vaporizes from the weld pool and if the vapour cannot easily escape, the pressure is built up to the vapour pressure of the metal. This vapour pressure is highly dependent on the temperature of the weld pool. For iron for example the pressures for 2600 K is $5 \times 10^3$ N/m$^2$ and for 3000 K is $5 \times 10^4$ N/m$^2$ [26].

This is an important part for the opening of the keyhole during welding. The vapour also exerts a pressure on the sides of the keyhole and prevents the keyhole from closure.

Recoil pressure

The recoil pressure is the pressure applied by the vaporized particles on the weld pool [26]. The recoil pressure is the driving force behind the opening of a keyhole. The recoil pressure is highly dependent on the power density. It can be described with equation 12.

$$p_r = \frac{W^2}{\rho_g Q A^2}$$

$W/A =$ power density [W/m$^2$] = power/area
$Q =$ amount of heat required to vaporise 1 kg of metal [J/kg]
$\rho_g =$ vapour density [kg/m$^3$]

Beam pressure

The beam pressure is different for plasma arc welding, electron beam welding and laser beam welding. For plasma arc welding the dominant pressure is due to the gas pressure of the plasma gas [26].

$$p_{b_{plasma}} = \frac{1}{2} \rho_g \langle \tau \rangle v^2$$

32
\( \rho_g \) = gas density [kg/m³]

\( T \) = temperature [K]

\( v \) = gas velocity [m/s]

For laser beam welding the beam pressure is caused by the radiation pressure of the photons and can be described with equation 14 [26].

\[
P_{b_{-}\text{laser}} = \frac{W}{Ac}
\]  

\( W/A \) = beam intensity [W/m²]

\( c \) = velocity of light [m/s]

For an electron beam, the beam pressure is caused by the electrons striking the metal surface the pressure can be described with the following equation [26]

\[
P_{b_{-}\text{electron}} = nm_e v
\]

\( n \) = number of electrons

\( m_e \) = electron mass [kg]

\( v \) = mean electron velocity [m/s]

**Gas flow**

The gas flow differs for different welding processes. For laser beam welding the gas flow is influenced by the cover gas flow, the external backing gas flow and an optional plasma control gas in CO₂ laser welding. The amount of gas flow and the velocity can vary. The flow of gas can exert a shear tension over the surface of the weld pool. For plasma welding this is a more significant factor where the plasma gas is able to create a keyhole as described above under beam pressure. For arc welding processes the effect of the shear stress is shown in figure 30.

![Arc Shear Stress](image)

Figure 30: Flow due to shear stress created by the gas flow in the arc, left the direction of the force, right the flow created [18].
To summarize the influence of the forces on the weld pool, table 6 is constructed. In this table, the different forces that can act on a weld pool for the different welding processes are shown. A score is given for the forces that are weak or not present (-), those that have little influence (0) and those that are dominant (+).

**Table 6: Overview table of the different forces dominant for the different processes**

<table>
<thead>
<tr>
<th></th>
<th>Laser welding</th>
<th>Laser welding</th>
<th>Plasma welding</th>
<th>Plasma welding</th>
<th>Electron beam welding</th>
<th>Electron beam welding</th>
<th>Upset welding</th>
<th>Flash welding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface tension on the sides of the weld pool</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Surface tension during welding in the weld pool</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Buoyancy</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gravitational pressure</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lorentz force</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Beam pressure</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
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<tr>
<td>Recoil pressure</td>
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<td>+</td>
<td>0</td>
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<td>-</td>
</tr>
<tr>
<td>Vapour pressure</td>
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<td>+</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Gas flow pressure</td>
<td>0</td>
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<td>+</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>External mechanical pressure</td>
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<td></td>
</tr>
</tbody>
</table>
2. Experimental

In this study the feasibility of welding thin strip material with low amounts of geometrical and metallurgical defects is described. Experiments were done at different facilities and with the cooperation of different people, universities and companies. In this chapter the different materials, joining methods and analyse techniques that were used are described.

2.1. Materials

Three different materials were used Ultrafort, Durimphy and Phytime. The latter two are or will possibly be used in the transmission push-belt of VDT. For this study it was most likely that only Phytime would be used, because this will be the material for the push-belts in the future. Durimphy is also of interest because this is the current material. None of these were available as strip material with the required rounded sides. Therefore another maraging steel, Ultrafort, is also used in the experiments. Later on in the study also Phytime and Durimphy were tested but these strips were cut from a large sheet and did not have the right dimensions on the sides. In section 2.6 an overview will be given of the different welding arrangements and materials that were used.

Ultrafort 1.6908

The Ultrafort was developed by Thyssen Edelstahlwerke AG, in the eighties of the 20th century. It is protected by a patent and for this reason only deliverable by ThyssenKrupp. It is a cobalt free martensitic steel with in general good corrosion resistance and a relative high toughness-strength combination. The general chemical composition is given in table 7. For this material it should be noted that no cobalt is present, this is replaced by chromium because it is a cheap substitute for cobalt, with chromium it was possible to obtain a martensite structure with the possibilities for precipitation hardening. In comparison with most maraging steels the Ni content is relatively low.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>Ti</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>8.5</td>
<td>4.5</td>
<td>8.5</td>
<td>0.5</td>
<td>Bal.</td>
</tr>
<tr>
<td>Max</td>
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<td>0.30</td>
<td>0.30</td>
<td>0.025</td>
<td>0.015</td>
<td>10.5</td>
<td>5.5</td>
<td>11.0</td>
<td>1.0</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

The chemical composition results in a martensitic microstructure [28] when air cooled. The martensite start temperature ($M_s$) is 116°C, the austenite start temperature is approximate 640°C and the austenite finish temperature is about 740°C. The strip was delivered with deburred and rounded edges. The dimensions of the thin strip are 8.8 mm wide and 0.4 mm thick, the strips were cut to a length of 40-60 mm with a Struers Labotom cutting machine.
**Durimphy**

Durimphy is an 18% Ni maraging steel that is produced by Imphy Alloys. It is applied in different advanced applications like rocket fins, ball bearing cages, springs for watches and within the push-belt of a continuous variable transmission. The chemical composition is shown in table 8. The characteristic elements present in Durimphy are nickel, cobalt, molybdenum, titanium, aluminium and iron. The strips have a width of 12.2 mm, a thickness of 0.360 mm and a length of 40-60 mm. The thin strips were cut from sheet material, the sides were ground for some experiments.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mg</th>
<th>S</th>
<th>P</th>
<th>Ni</th>
<th>Co</th>
<th>Mo</th>
<th>Ti</th>
<th>Al</th>
<th>Cr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td>0.05</td>
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<td>Bal</td>
</tr>
<tr>
<td>Max</td>
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<td>0.20</td>
<td>0.20</td>
<td>0.010</td>
<td>0.007</td>
<td>19.0</td>
<td>10.0</td>
<td>6.0</td>
<td>0.7</td>
<td>0.15</td>
<td>0.25</td>
<td>bal</td>
</tr>
</tbody>
</table>

The microstructure mainly consists of martensite. Some TiC and TiN inclusions are present, and appear as orange particles, when etched with Adler's reagent The martensite start temperature upon cooling of 300°C/h is 194 °C, the martensite finish temperature is 146 °C and the austenising temperature $A_{c3}$ lies at 746°C.

**Phytyme**

Phytyme is an 18% Ni maraging steels that is also produced by Imphy Alloys. It is recently developed as an improvement of the Durimphy for the application of the CVT push-belt. The chemical composition is shown in table 9. The chemical composition of the Phytyme alloy is nominally titanium free. The major contribution of titanium to strengthening in Durimphy is compensated by an increase in the cobalt content. Aluminium is also absent in the alloy, this will reduce the presence of aluminium oxides in the material. The microstructure that is formed is similar to Durimphy, a martensitic structure but without TiN inclusions. The material was welded in the cold rolled state from strips with a width of 12.2 mm, a thickness of 0.4 mm and length of 40-60 mm. The martensite start temperature is 206 °C, the finish temperature is 134°C and the $A_{c3}$-temperature is 756°C.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Ni</th>
<th>Co</th>
<th>Mo</th>
<th>Ti</th>
<th>Al</th>
<th>Cr</th>
<th>Fe</th>
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<tr>
<td>Max</td>
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<td>0.10</td>
<td>0.20</td>
<td>0.005</td>
<td>0.007</td>
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<td>17.0</td>
<td>5.6</td>
<td>0.025</td>
<td>0.04</td>
<td>0.25</td>
<td>bal</td>
</tr>
</tbody>
</table>
2.2. Welding arrangements

For welding a butt joint with a minimum of irregularities at the start and at the end of the seam different effects need to be taken in account. These are the movement of material due to the forces that act on the weld pool as well as the differences in forces due to the different geometry's at the start and at the end in comparison with the middle of a butt joint. For welding a butt joint extra tools can be used to successfully reach the aim of this research. These different ideas are described below, and sorted into different configurations for welding, the so called welding arrangements. All of the experimental arrangements are tested with thin flat strips instead of rings.

Plain butt weld

The setup of a butt weld is shown in figure 31. Two ends of the workpieces are placed together and a joint is made over the interface of the two ends. With a fusion welding process and for a fully penetrated joint the material needs to be melted over the full thickness. This is a criterion for the welding process that is selected. A first challenge is to control the heat input during welding. The second challenge lies in the size of the weld pool and the surface tension acting on the surface, this can work as a contracting force and leave a crater at the end of a seam as shown in the example of the initial tests, see figure 14.

![Figure 31: Butt joint configuration of two strips, the adjacent interfaces are melted and form the joint.](image)

Physical copper limits

To reduce the effects of the differing geometry of the beginning and end of the seam several welding arrangements were designed. The use of copper limits is one of these arrangements. The strips are set up in a butt weld arrangement and at the run-on and run-off of the seam a copper limit is placed as shown in figure 32. Two different effects can happen at the copper limits. Firstly the material in the weld pool can be attracted to the copper limit as a result of a possible decrease in surface free energy; the contraction of the weld pool is prevented in that case. Secondly the
liquid material in the weld pool can be quenched by the extraction of heat out of the weld pool. The heat extraction can solidify the material directly upon contact and in this way produce a geometry with a non-contracted end. Extra options when this technique works out successful are changing the shape of the copper limits and in that way changing the geometrical properties after welding. Three different copper limits were used; a vertical copper limit, a slanted copper limit and a flat copper limit (see figures 32 to 34). The limits and the workpieces were placed in the clamping device shown in figures 38 and 39.

Figure 32: Dimensions of physical vertical copper limit with flat end, the limit is 5 mm thick. The red arrow directs the welding direction.

Figure 33: Dimension of physical slanted copper limit with diagonal surface, the limit is 5 mm thick. The red arrow directs the welding direction.

Figure 34: Dimensions of physical flat copper limit of 0.5 mm thick. The red arrow directs the welding direction.

This solution could be feasible, but there are two limitations. Firstly the amount of material movement over the seam could be significant and cause irregularities. A second limitation of this process is the contact between the weld pool and the copper. The melting temperature of pure copper is 1083°C this is lower than the melting point of the maraging steels. It is likely that some copper would be dissolved in the weld pool, which is unacceptable. An alternative for the copper needs to be found if this is a limiting factor.

Run-on and run-off tabs

The arrangement of welding with run-on and a run-off tabs can be applied for fusion welding processes. It uses strips of the same material at the start and at the finish of the joint, see figure 35. These tabs need to be removed after welding. The finished product is a ring without the run-on and run-off tabs. The extra strips used
prevent a lack of material at the start and end of the joint. One challenge will be to have no gap between the workpieces and the tabs during welding. A gap between the tab and the workpieces will increase the chance for the creation of holes in the seam. A limitation of the arrangement will be the separation of the workpieces from the run-on and run-off tabs. These will need to be cut or broken carefully, to prevent introducing new defects, furthermore to meet the geometrical requirements the ring needs a mechanical post-treatment. A second disadvantage is that the run-on and run-off tabs are consumables.

Figure 35: Welded strips in a butt joint configuration, with a run-on tab and a run-off tab

**Multiple ring welding**

As the aim is to be able to weld large numbers of rings without irregularities at the sides, the most efficient way of welding is preferable. If the arrangement of welding with a run-on and a run-off tab is successful, an opportunity might be the arrangement of welding multiple rings in one batch. By placing more rings behind each other, a nearly continuous process can be designed with no consumables. It is an arrangement that can be combined with the fusion welding processes. A challenge will be formed by the precise alignment of the workpieces to prevent the creation of holes to prevent defects due to misalignment. The idea is shown schematically in figure 36. A structural limitation is formed by the arrangement itself; the rings need to be separated after welding.
External pressure perpendicular to the joint interface

An extra arrangement of positioning and clamping of the workpieces is used with resistance welding. To have a good contact between the interfaces of the different workpieces an external pressure is applied perpendicular to the welding direction see figure 37. With resistance welding it is common to have a high pressure that deforms the zone at the interface. The material at the interface is heated, deformed and pushed out. This material needs to be removed to reach a sufficient surface quality.

For fusion welding processes this idea might be used as well to fill the lack of material at the end of the seam. It has certain challenges, for instance as the material is melted with fusion welding processes, a pressure is applied, and the fluid cannot transfer these amounts of forces, this will probably result in the fluid flowing to the topside and underside of the strips. This can result in geometrical defects at the surface that need to be removed again. This arrangement is only tested with resistance welding.

Figure 37: Two strips in a butt joint configuration, the arrows mark the direction of the force that is applied.

2.3. Welding processes

Different welding processes were used, including laser beam welding, electron beam welding, plasma arc welding and resistance welding processes. These are described in this section.

Laser beam welding

The workpieces were clamped in a device as shown in figures 38 and 39. In these figures it can be seen that the workpieces were clamped by a vertical force from above, applied by a steel strip connected with two clamps. The cover gas was added from the top by a copper nozzle (diameter 8 mm), this was fixed to the laser beam delivery system such that the distance from the focus spot is constant. The
backing gas was flowing from the bottom through a perforated copper tube. The gas flow rate varied from 4 to 40 l/min.

Figure 38: Clamping device in top view

Figure 39: Clamping device with clamps, backing gas tube and cover gas tube

Continuous wave

For welding in continuous mode two laser sources were used. The first laser source was the HLD 1001.5 from Trumpf. This is a disc laser with as a light source element Yb:YAG-crystal. The wavelength of the laser source is 1.07 µm and the maximum power 1500 W. All of the welds were made with a focus lens with a focal distance of 150 mm and a collimator lens with a focal length of 200 mm. Three fibers were used the 150 µm, 300 µm and 600 µm fibres, forming spot sizes of 112.5 µm, 225 µm and 450 µm respectively. The cover gas used was argon.

The second continuous wave laser source was the HL3006D from Haas. The laser light source is a Nd:YAG crystal (Neodymium-doped yttrium aluminum garnet crystal). The maximum output power is 3000 W, for all of the joints made with this laser a 600 µm fibre was used, a collimator lens of 200 mm and a focus lens with a focal length of 150 mm, this produced a spot diameter of 450 µm. On the laserhead a cross jet was placed. This cross jet protects the cover glass (which protects the lens) from fumes, spatter droplets and the plasma plume. The cross jet works with compressed air blown in the direction parallel to the lens.

The cover gas and backing gas used with the experiments on the HL3006D was argon (99.996% purity). For most of the experiments the angle of the laser beam to the workpieces was 90° like all of the other laser beam welding experiments, some of the experiments were done with the laser beam under an angle of 75° and the moving direction was leading.

Pulsed mode

In this study the welds were made with a pulsed mode laser, the HL 204 P from Haas/Trumpf. All of the welds were made with a 400 µm fibre, a collimator lens with a focal length of 200 mm and a focus optic with a focal distance of 150 mm. The
focus spot had a diameter of 300 μm. The cover gases used were Ar and He. All the strips were welded from side to side. Every weld therefore has one run-on and one run-off of the laser beam onto the material. Most of the welds were performed bead-on-plate.

**Shadow welding**

Shadow welding is the name for a special way of welding where a weld is made with a single high energy pulse. The pulse is directed by a scanner optic over the surface of the workpieces, this scanner moves the spot of the laser. As this scanner is mainly a small moving mirror, very high welding velocities can be achieved.

In this study the welds were made with a pulsed mode laser, the FLS 1042 C from Lasag. The wavelength of the Nd:YAG-laser is 1064 nm and the maximum peak power is 10 kW. For this laser one kind of fibre with a 400 μm diameter was available. The maximum pulse length was 50.0 ms, the cover gas was Argon. The welding speed was controlled by a scanner optic and varied from 200 mm/s up to 1600 mm/s. The software for the scanner was In Script 2.0 developed by Arges.

**Line focus**

The LDL 40-1500 from Laserline is a direct diode laser. The laser was able to work in a continuous and a pulsed mode. The wavelengths of the laser are 808 nm, 940 nm and 980 nm and the maximum power 1500 W. This laser made no use of a fibre to guide the laser beam. The lens had a focus distance of 200 mm. As the beam profile was linear the focus spot had a length of 14 mm and a width of 0.6 mm. With this wide focus spot it was not needed to move the spot. The spot could melt the seam over the total width, when sufficient energy was put into the material.

The joints made with this laser were performed in conduction mode, due to the low energy intensity at the focus spot the temperature in the weld pool was not high enough to create a keyhole. The focus spot of the laser was on a fixed position of the workpiece. The covergas used was argon and all of the welds were done bead-on-plate (i.e. a weld on the middle of one workpiece instead of creation of a joint between two workpieces).

**Electron beam welding**

The electron beam welding experiments were done by the RTWH Aachen University, ISF Welding and Joining Institute. The experiments were done on the material Ultrafort 6908. The welding machine used was a Steigerwald Strahltechnik with a maximum acceleration voltage of 150 kV. The exact focus spot size was not reported. The experiments were done under vacuum, exact pressures were not reported. No features such as pre-heating and or post-heating were tested.
Plasma welding

Plasma arc welding experiments were done with E.Willems at WIK. The plasma experiments were carried out with direct current electrode negative with a sharp tip electrode. The current source used was a Plasmafix 50E from Séchéron. The parameters are shown in table 10, a critical parameter missing is the voltage drop over the two electrodes without this parameter it is not possible to estimate the heat input. All the experiments were performed on Phytime material.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current [A]</td>
<td>8.0</td>
</tr>
<tr>
<td>Velocity [mm/s]</td>
<td>0.8</td>
</tr>
<tr>
<td>Voltage drop between the electrodes [V]</td>
<td>Not reported</td>
</tr>
<tr>
<td>Plasma gas flow Ar purity: 99.996 % [l/min]</td>
<td>0.3</td>
</tr>
<tr>
<td>Shielding gas flow Ar 93% and 7% H₂ [l/min]</td>
<td>5</td>
</tr>
<tr>
<td>Backing gas flow Ar 93% and 7% H₂ [l/min]</td>
<td>6</td>
</tr>
<tr>
<td>Diameter plasma gas nozzle [mm]</td>
<td>1.0</td>
</tr>
<tr>
<td>Diameter shielding gas nozzle [mm]</td>
<td>7.5</td>
</tr>
<tr>
<td>Tip angle of electrode [°]</td>
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</tr>
<tr>
<td>Diameter electrode [mm]</td>
<td>2</td>
</tr>
<tr>
<td>Angle between electrode and seam (leading) [°]</td>
<td>80</td>
</tr>
</tbody>
</table>

The experimental setup is shown in figure 40 and 41. Here the clamping device, torch and current source are shown. Figure 42 and 43 show the electrode and the plasma gas nozzle.
Resistance welding

Resistance welding tests were carried out at three different companies, Ideal, Strecker and Bihler, all located in Germany. These companies build resistance welding machines, Ideal used flash butt welding, Bihler and Strecker used resistance upset welding and Bihler also performed the resistance welding with some overlap.

The process of flash butt welding was tested at Ideal. Ideal used the BAS050 see figure 44. The exact process parameters were not delivered by Ideal.

For the upset welding experiments Ultrafort was used, 7 samples were welded by Strecker. No parameters were reported for these experiments. The samples will only show the feasibility of upset welding.

The parameters of the experiments done by Bihler for upset welding were reported. Bihler used a resistance welding machine with a high frequency converter with a frequency of 5000 Hz, type ET70. The heat input profile is shown in figure 46, welding voltage was 1.51V and the welding current was 1.26 kA. The first of the two steps was probably done to flatten the interfaces of the workpieces. In the second step the welding force of 540 N was applied. The material of the electrodes is
unknown, but expected to be a copper alloy which is commonly used due to its heat and current carrying transport characteristics. The layout is shown in figure 45.

The other experiments done by Bihler were best described as a combination of resistance spot welding and mash seam welding ("mash resistance welding"). The workpieces were placed over each other as in a lap joint, and then two electrodes were placed on the top and the bottom of the overlap as shown in figure 47. These fixed electrodes were at least as wide as the strips. While the welding current was applied an extra force was applied with the am to flatten the surface. The welding parameters were not given by Bihler. For two samples the seam was extra deformed with an extra force applied on the surface of 12 and 18 tons.

**2.4. Mechanical and metallurgical evaluation**

The mechanical properties over the seam are preferred to be equal on every location as the thin strips that are welded to rings need to be rolled out. As the material is locally melted (the weld pool) and locally heat-treated (heat affected
zone), the microstructure is expected to be significantly different from the base metal. This has its influence on the mechanical properties. For the mechanical and metallurgical evaluation different measurement methods were used. The hardness was measured and the metallurgical properties were studied by optical microscopy. For some samples the microstructure and hardness were studied after annealing for 15 minutes at 880°C.

**Hardness**

Hardness is defined as the ability of a material to resist permanent indentation or deformation when in contact with an indenter under load. The microhardness was tested with a Vickers indenter, this is a square pyramidal indenter with a top angle of 136°. For Vickers microhardness this load is between 1 and 1000 g. For testing the hardness the Shimadzu HMV-2 and a Beuhler microhardness tester were used. The load was applied for 10 s and was 100 g for 0.1HV, 500 g for 0.5HV and 1000g for the standard HV. The sizes of the indents were measured with a microscope combined with a camera and calculated with the system software.

**Sample preparation**

The samples were embedded in the transverse and some in the longitudinal direction. For the cutting of the samples two grincing machines were used a Streurs Labotom and a Streurs Secotom 10. Samples were embedded with Struers Isofast, Struers Durofast and Technovit 4000. These were ground and polished in different steps: 120 μm until plain > 9 μm> 3 μm >1 μm or 0.25 μm. For revealing macrostructure and microstructure, five different etching reagents were used.

**Table 11: Different etching reagents used**

<table>
<thead>
<tr>
<th>Reagent</th>
<th>Composition</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adler’s reagent</td>
<td>4 g copper ammoniumchloride 25 ml H₂O 15 g FeCl₃ 50 ml HCl</td>
<td>2 – 3 seconds</td>
</tr>
<tr>
<td>Fry’s reagent no.1</td>
<td>480 ml H₂O 150 ml ethanol 8 g CuCl₂ 150 ml HCl</td>
<td>50 seconds</td>
</tr>
<tr>
<td>Marble’s reagent</td>
<td>20 g CuSO₄ 100 ml HCL 100 ml H₂O</td>
<td>15 seconds</td>
</tr>
<tr>
<td>Kalling’s reagent nr.2</td>
<td>5 g CuCl₂ 100 ml HCl 100 ml ethanol</td>
<td>50 – 60 seconds</td>
</tr>
<tr>
<td>Nital (depending on the %)</td>
<td>1 - 10 ml HNO₃ 90 – 99 ml ethanol</td>
<td>50 seconds</td>
</tr>
</tbody>
</table>
Microstructure

The metallurgical characteristics from the transverse sections of the heat affected zone and the fusion zone were analysed and for the longitudinal sections the fusion zone was analysed. For the pictures, different microscopes were used, Olympus BX60M, Leica MZ125 and Leica MEF4M the latter two in combination with a Leica DPC320 camera and Leica IM50 4.0 software. These had the possibility for enlargements from 8x up to 1875x.

2.5. Geometrical evaluation

For the application for which this study was undertaken, the geometrical criteria for the facets (side of the strips) are high. In the push-belt, the joint is loaded dynamically for many cycles, the irregularities act as stress concentrators and can initiate fatigue cracks. In the unaged state, the allowed defect depth must be smaller than 50 μm. This challenge is faced when welding rings and therefore the defects should be quantified. The ultimate goal is to have no irregularities on the facet. For measuring and categorising the defects two methods are used, photos of the geometry under a calibrated optical microscope and the use of white light interferometry.

Optical microscope

From the samples photos were taken and within these pictures the size of the defects could be measured for the parts that were in focus. The microscopes used are the Olympus BX60M, Leica MZ125 and Leica MEF4M the latter two in combination with a Leica DPC320 camera and Leica IM50 4.0 software.

White light interferometry

White light interferometry is a technique that can perform non-contact, 3D surface roughness and topography measurements. It uses light to measure the surface heights in almost the same way as an optical microscope. This can be done with a precision in the order of nanometres to several millimetres. In a profiler, white light is passed through a beam splitter, which directs the light to the sample surface and a reference mirror see figure 49. When the light reflected from these two surfaces recombines, a pattern of interference fringes is formed. Maximum fringe contrast occurs at the best focus position for each given point on the sample. The measurement head is moved vertically such that each point on the surface passes through focus. A series of algorithms is applied to precisely map the height of each point on the surface [30].
From this data a 3D-image from the surface can be created. This data forms a powerful tool to visualise the surface. Different standard roughness coefficients can be calculated examples are the $R_s$, $R_q$ and $R_t$ (average roughness, root mean square of the roughness profile and the maximum difference in height over the surface respectively).

The welds were analysed with the Wyco NT1100 see figure 48, with different optical magnifications (2.5, 5 or 10 times). From these data 3D topographical figures were produced. These figures give a good indication for the surface quality and the edge defects. With these figures it is possible to compare the values from the different processes.

2.6. Overview of experiments

In this project different materials were used, Ultrafort, Durimphy and Phytime, these materials were not all used in every experiment. In table 12 an overview is shown for the different materials that were used with the different welding arrangements. The use of Phytime was desired as this material should show a significant life time improvement in the application of the push-belt. The influences of the welding processes on the different materials are discussed in the next chapter.
Table 12: Overview for the experiments done with the different welding arrangements, welding processes and materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Welding Process</th>
<th>Welding Arrangement</th>
<th>Physical capacity limits</th>
<th>Run-off and run-off limits</th>
<th>Multiple rings welding</th>
<th>External pressure after welding</th>
<th>Lap joint configuration with extra deformation force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duraloy</td>
<td>Uilleton</td>
<td>+</td>
<td></td>
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</tr>
<tr>
<td>Duraloy</td>
<td>Pulsed mode LFW</td>
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<tr>
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<tr>
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</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>Duraloy</td>
<td>Lap joint welding with LFW</td>
<td>+</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Duraloy</td>
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</tr>
<tr>
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<tr>
<td>Duraloy</td>
<td>Uilleton</td>
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<td>Duraloy</td>
<td>Pulsed mode LFW</td>
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</tr>
<tr>
<td>Duraloy</td>
<td>Continuous wave LFW</td>
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</tr>
<tr>
<td>Duraloy</td>
<td>Line focus with LFW</td>
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<td></td>
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</tr>
<tr>
<td>Duraloy</td>
<td>Shadow welding with LFW</td>
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<td></td>
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</tr>
<tr>
<td>Duraloy</td>
<td>Lap joint welding with LFW</td>
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<tr>
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<td>Electron beam welding</td>
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<tr>
<td>Duraloy</td>
<td>Plasma arc welding</td>
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</tbody>
</table>
3. Results

The results are split into two parts, in the first part (section 3.1 to 3.6) the influences of the different welding arrangements on the geometry will be presented and in the second part the influences of the different welding processes on the microstructure and the microhardness of the different materials are described (section 3.7). From the results a prognosis for the possibility of low defect strip welding can be derived.

Several welding processes were used within the study to test the feasibility of strip welding with small geometrical and metallurgical defects. These processes include the different laser beam welding processes (see section 2.3), electron beam welding, plasma arc welding, upset welding, flash welding and "mash resistance welding".

3.1. Laser beam welding

Four different laser beam welding processes were tested; pulsed mode laser beam welding, shadow welding, laser beam welding with a line focus over the total width of the seam and continuous wave laser beam welding. These processes were all tested with several experimental arrangements to influence the weld bead and with different materials as shown in table 12. For these processes and arrangements it was expected that they could have a positive result on the geometry of the seam.

3.1.1. Pulsed mode

With pulsed mode laser beam welding two different arrangements were tested, a plain butt weld arrangement and welding with physical (copper) limits at the start and end of the seam. The tests were performed on Ultrafort strip material. Most of the tests were done bead-on-plate.

3.1.1.1. Plain butt weld arrangement (bead-on-plate)

First the possibilities with a pulsed mode laser are shown for a plain butt weld arrangement. With these tests it is expected that a good fully penetrated weld can be made where the surface shows the overlap of the pulses. A bead-on-plate (BOP) weld is shown in figures 50 and 51, this was made with $P=600$ W, $F_z=60$ Hz, $v=13.3$ mm/s and $t_{\text{pulse}}=4$ ms. The fully penetrated weld shows a regular pattern see figure 52, besides the defects on the run-on (start) and run-off (end), the few spatter droplets on the underside are the only defects visible form the visual inspection (see figure 53). The width of the weld pool on the topside was 710 to 750 μm and on the underside about 300 to 350 μm.
The surface geometry was measured using an optical profiler see figure 54. With this technique the surface geometries of the different welding processes can be compared. The surface has irregularities over the whole seam as a result of the separate pulses and the heights of the irregularities are up to 25 \( \mu \text{m} \). The coloured picture on the left shows a map of the total area (1.8 by 2.3 mm) and the x and y profiles (resp. red and blue) show the height map over the seam at the location of red and blue surface profile lines.

The X-profile shows the distance between the start of the different pulses every 207 +/- 24 \( \mu \text{m} \), the surface contains sharp angles between the different pulses and the pulses and weld pool. From the Y-profile the width of the seam can be determined and is 740 \( \mu \text{m} \).
Figure 54: White light interferometer measurement of the top surface of a pulsed mode laser joint, the x profile (red line) gives the irregularities in the length of the seam, the y-profile shows the tilted positioning of the strips and the height difference of the seam to the base metal (A27: BOP, P=600 W, $F_z=60$ Hz, $t_{pulse}=4$ ms, $V_{weld}=13.3$ mm/s).

A close-up of the run-on and run-off regions is shown in figures 55 and 56. In these close-ups it can be seen that there was a defect at the end of the seam; for the run-on the size was 30 to 40 μm and for the run-off the size was about 160 μm. Defects larger then 50 μm are unacceptable. These defects are most likely caused by the surface tension that contracts the liquid, this is further discussed chapter 4. The term contraction is used to denote this defect.

Figure 55: Run-on of pulsed seam a defect of about 30-40 μm is present (A33, P=600 W, $F_z=60$ Hz, $V=13.3$ mm/s and $t_{pulse}=4$ ms).

Figure 56: Run-off of pulsed mode seam with a defect of about 160 μm deep (A33).
Significant improvements for reduction of these defects are not expected with other parameters or with a different material like Durimphy or Phylime. To further improve the welds a different experimental arrangement was tested.

3.1.1.2. Welding with physical copper limits

One of the ideas to prevent the contraction of the seam at the start and the end is to use physical limits on the sides of the seam. This is performed with two out of the three different copper limit shapes, see figures 32 and 33. From the influence of these limits it is expected that the weld pool can be attached to the copper, and in this way prevent a defect on the run-on and run-off. The shape of the limit, vertical or slanted could have a different influence on the shape of the run-on and run-off as the interface changes where the seam is attached to the surface.

The pulsed mode seam showed the same general features as in the previous experiments, fully penetrated seams and some spatter droplets appeared on the underside around the seam. The general surface geometry was as described above.

The copper limits on the run-on produce a flat surface and left no significant defect at the side facet (see figures 57 and 58). The run-on does not have the same shape as the rest of the facet from the strip, but it does not show a lack of material.

![Figure 57: Run-on of seam (A42, BOP, P=704 W, F_z=60 Hz, v= 13.3 mm/s and t_{pulse}=2.5 ms) with flat physical copper limit, the run-on is flat without extra defect.](image)

![Figure 58: Underside of run-on of sample A42 welded with a flat physical limit, some oxidation and spatter droplets are present.](image)

For the run-off the influences of the limits are shown in figures 59 to 62 for the vertical limit (figure 32) and in figures 63 and 64 for the slanted limits (figure 33). The vertical limits show that the weld pool is not contracted. At the run-off it can be seen that the weld pool is oscillating after a pulse impacted the surface (figure 62). The crater depth was measured and is in the order of 60 µm. The weld pool solidifies against the copper, this is observed for the vertical limits and the slanted limits. Comparing these with joints made without copper limits (figures 55 and 56), it can be seen that the weld pool is influenced by the shape of the limits. The position of the
solidified front of the weld pool lies underneath the strips and the front has the same angle as the physical copper limits.

Figure 59: Topside of the run-off of a pulsed mode laser welded sample A30 (BOP, P=600 W, f=60 Hz, t_pulse=4 ms, V_weld=13.3 mm/s) with a vertical copper limit. Contraction has not taken place.

Figure 60: Underside of the run-off of the pulsed mode laser welded sample BOP (A30), with a vertical copper limit.

Figure 61: Side view of the run-off of the pulsed mode joint (A30), with a vertical copper limit, the surface edge is irregular.

Figure 62: The run-off (A18, BOP, P=576 W, f=60 Hz, t_pulse=4 ms, V_weld=13.3 mm/s, vertical copper limits) viewed under an angle of about 30 degrees, a lack of material in the thickness is still present.
3.1.2. Shadow welding

The second laser welding process examined is shadow welding, the welding process makes use of a high energy pulsed laser in combination with a scanner, with this process it is possible to weld with extremely high velocities. With this welding process, different welding arrangements were tested; welding with a butt weld bead-on-plate (BOP) setup, welding with the laser beam moving in one direction (BOP), welding with the use of copper limits on the run-on and run-off (BOP), welding with two pulses with an overlap in the middle (BOP), welding while moving the laser beam in multiple directions (BOP) and welding the material on both sides of the strips. Only The last idea was tested in a butt weld configuration with Durimphy, the other possibilities were tested on Ultrafort.

With this welding process a dynamic weld pool can be expected due to the high velocities but the exact behaviour could not be predicted. Therefore different arrangements were examined with the intent to influence the shape of the weld pool during welding.

3.1.2.1. Plain butt weld arrangement (bead-on-plate)

In the first welding arrangement the beam was moved from one side to the other side of the material (bead-on-plate). The aim was to perform a fully penetrated weld over the total length of the seam. The influence of the welding velocity on the quality of the seam was investigated. The best parameters found for different velocities are shown in table 13.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Power [W]</th>
<th>Velocity [mm/s]</th>
<th>Pulse time [ms]</th>
<th>Heat input [J/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L 18</td>
<td>1500</td>
<td>200</td>
<td>50</td>
<td>7500</td>
</tr>
<tr>
<td>L 17</td>
<td>2300</td>
<td>400</td>
<td>25</td>
<td>5750</td>
</tr>
<tr>
<td>L 43</td>
<td>4400</td>
<td>800</td>
<td>12,5</td>
<td>5500</td>
</tr>
<tr>
<td>L 44</td>
<td>9500</td>
<td>1600</td>
<td>6,67</td>
<td>5936</td>
</tr>
</tbody>
</table>
The results are shown in figures 65 to 80. The seam qualities for the velocities up to 400 mm/s were acceptable in the middle of the seam. The seam made with a velocity of 200 mm/s in figure 65 was fully penetrated and the seam made with a velocity of 400 mm/s was fully penetrated except for the last 100 μm. No spatter droplets or significant oxidation were present on the weld. The run-off showed a defect in the centre of the weld bead, the height of the weld pool decreased at this position (figure 73).

What can be seen in general is that with a higher velocity and a higher energy input, the defects on the run-on and run-off became larger. At the run-off more material is missing and at the run-on more material is piling up. The weld made with 800 mm/s showed a major defect of the run-on where a ball of metal was formed (figures 67 and 71). For the welds made with a velocity of 1600 mm/s, no material was left in the seam (figures 76 and 80).
Run-on topside

- $v=200 \text{ mm/s, } P=1500 \text{ W (L18)}$
- $v=400 \text{ mm/s, } P=2300 \text{ W (L17)}$
- $v=800 \text{ mm/s, } P=4400 \text{ W (L43)}$
- $v=1600 \text{ mm/s, } P=9500 \text{ W (L44)}$

Defect

500 µm

Figure 65: Run-on topside of sample L18

Defect

500 µm

Figure 66: Run-on topside of sample L17

Ball

Material blown away

500 µm

Figure 67: Run-on topside of sample L43

Run-on underside

Defect

500 µm

Figure 69: Run-on underside of sample L18

Defect

500 µm

Figure 70: Run-on underside of sample L17

Ball

No full penetration

500 µm

Figure 71: Run-on underside of sample L43

Figure 72: Run-on underside of sample L44
v=200 mm/s, P=1500 W (L18)  
Run-off 
topside

v=400 mm/s, P=2300 W (L17)  

Figure 73: Run-off topside of sample L18

v=800 mm/s, P=4400 W (L43)  

Figure 74: Run-off topside of sample L17

v=1600 mm/s, P=9500 W (L44)  

Figure 75: Run-off topside of sample L43

Run-off 
underside

Figure 76: Run-off topside of sample L44

Figure 77: Run-off underside of sample L18

Figure 78: Run-off underside of sample L17

Figure 79: Run-off underside of sample L43

Figure 80: Run-off underside of sample L44
From the experiments with shadow welding with the movement of the beam in one direction, no satisfactory results were obtained. Large defects were present at the run-on and on the run-off of the seam. These became larger with higher powers and higher welding velocity. The best results were obtained with lower velocities. The lowest velocity tested was 200 mm/s, this velocity was limited by the maximum pulse time of the laser (50 ms) as a distance of 10 mm needed to be covered with one pulse.

3.1.2.3. Welding with physical copper limits

It was expected that the defects that were present on the run-on and the run-off, could be solved with physical copper limits. It was expected that the effects of the physical limits would be comparable with what was seen in the pulsed mode experiments. Tests were done in a bead-on-plate arrangement with two types of physical copper limits; vertical limits see figure 32 and flat limits see figure 34.

Unfortunately, the seam quality was comparable to the experiments performed without copper limits. The seams showed in general little oxidation and in the middle of the seam close to the run-off a decrease in height was present. From a geometrical point of view the best results were obtained with the flat copper limit for the run-on as no lack of material was present. For the run-off none of the experiments done showed any influence of the copper limits. All of the tests showed for the run-off similar results to those presented in figures 73 and 77.

3.1.2.3. Welding with two consecutive pulses

A third way of butt welding is by joining the strips using two consecutive pulses with an overlap in the middle (i.e. a two step welding arrangement). This was done again with the aim to create a homogeneous distribution of material over the total width of the seam. The experiments were done with Ultrafort in a bead-on-plate configuration. On the sides of the Ultrafort strips flat copper limits were placed. The pulses were started from opposite edges of the material toward the middle of the thin strips, this experimental arrangement did not have a run-off like previous experiments but it has a run-on at both edges.

The results of the two separate pulses are shown in figures 81 and 82. The pulse shape is shown in figure 83. The seams were fully penetrated over half the width of the strips and visual inspection showed no oxidations or major defects. The sides of the seam did not show a defect due to a lack of material and showed similar results to those obtained during the experiments made with the flat copper limits. From these results the experiments were continued and the pulses were placed in overlap.
In figures 84 and 85 the middle of a sample is shown of an experiment where overlapping pulses were used. The power profile is shown in figure 86. With this seam only little oxidation was present on the underside of the seam, the seam was fully penetrated and the run-on did not show any lack of material. Figures 84 and 85 show that it is possible to make a weld fully penetrated with an overlap of the separate pulses. No parameters were found that gave reproducible results. The difficulty was to prevent the creation of a hole at the overlap of the consecutive pulses. A net material displacement was found towards the start of the seam.
3.1.2.4. Welding with the laser beam moving in three steps

As the material was displaced to the sides of the strips it was expected that better results could be obtained when the laser beam was started from the middle of the strip towards the side, then back to the second side and ending in the middle of the seam as shown in figure 87. To be able to analyze the three steps process, the experiments were split into the three individual steps. The first step is from the centre to the edge, secondly from one edge to the opposite edge and lastly the beam was moved from the edge to the centre. All the tests were performed in a bead-on-plate configuration.

![Figure 87: Movement of the beam during the three step welding process with the Lasag FLS 1024C](image)

**Step one** - The aim was again to achieve a homogeneous distribution of material over the seam after step 3. From the previous tests it was found that an excess of material appeared at the start of the seam. By welding in multiple directions the possibility for creating an equal distribution was tested. The result of only step 1 is shown in figures 88 and 89. In these figures it can be seen that at the side of the strip a lack of material was present. In the middle of the seam (at the start of the beam motion) the material was pilled up above the surface. This material could be redistributed in step 2 and 3.

![Figure 88: Sample L78, step one of three, P=2250 W and V=400 mm/s](image)

![Figure 89: Underside of sample L78, step one of three, P=2250 W and V=400 mm/s](image)

**Step two** - The two steps were done with the same pulse. Considerable testing was performed with different pulse shapes, the energy at the different positions of the seam were varied. Often a hole appeared in the seam, this was partly prevented by reducing the welding power, the amount of reduction of the laser beam power was limited as a full penetration of the seam was still required. The main
difficulty with this process step is the movement of material that takes place. The material did not achieve a homogeneous distribution during step 2 see figures 90 and 91. A pile-up and undercut are indicated by the arrows. The parameters are shown in figure 92.

![Figure 90: Topside of edge 1, step one and two (L96)](image)

![Figure 91: Topside of edge 2, step one and two (L96)](image)

![Figure 92: Energy input for L96, beam moving from the middle to the outside (5 mm) and then to the other outside (15 mm) at v=400 mm/s](image)

*Step three* - The maximum pulsetime of 50 ms was used at a welding velocity of 400 mm/s to make step one to three. A result is shown in figures 93 to 97. The parameters are shown in figure 98.

![Figure 93: Sample L131, edge 1, topside](image)

![Figure 94: Sample L131, edge 1, underside](image)

![Figure 95: Sample L131, edge 2, topside](image)

![Figure 96: Sample L131, edge 2, underside](image)
Figure 97: Sample L131, centre, topside

Figure 98: Energy input for sample L131, beam moved from the middle to edge 1, to edge 2 and back to the middle with \( V = 400 \text{ mm/s} \)

The weld did not show any oxidation, but was not fully penetrated due to the sensitivity for the creation of holes in the material. No homogeneous distribution was achieved. The sensitivity for the creation of holes was high, as it was when welding with two pulses. The possibility to weld a fully penetrated seam with an equal material distribution was not proven for the three step welding arrangement.

3.1.2.5. Welding on both sides of the strip

With the previous experiments it was observed that the defects at the run-on and run-off were limited when the weld was not fully penetrated. This phenomenon could be used in a positive way when a weld is made on both sides of the strips without a full penetration. The welding directions on the different sides of the workpieces are opposite to each other to limit the displacement of material over the seam. If the parent material limits the displacement of material in the fluid, a joint can be made over the total width of the seam. The arrangement was tested with Durimphy in a butt weld configuration. To influence the weld pool, flat physical copper limits were placed on the sides. The side of the Durimphy were not specially treated after cutting with a result that the material had no rectangular edges.

Only a few tests were done with this arrangement. Results are shown in figures 99 to 102, the samples showed a seam without oxidation, no cracks and no large irregularities in the seam. The sizes of the gaps at sides of the material were significantly reduced when compared with figure 65. The displacement over the seam towards the run-on was still present, at the run-off the material showed an undercut of about half of the thickness. The parameters are shown in table 14.

<table>
<thead>
<tr>
<th>Table 14: Parameters of welding on both sides of the strip</th>
</tr>
</thead>
<tbody>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>L231 (Durimphy)</td>
</tr>
</tbody>
</table>

63
With the arrangement of welding on both sides of the strips the best results with shadow welding were achieved. No major pile-up of material was found and the defect size at the facet was 0.1 - 0.2 mm, this is still unacceptable. The main problem with the shadow welding was the displacement of material over the seam. This phenomenon made it impossible to create a seam with a homogeneous distribution for thin strip welding. No solutions were found to solve or compensate for this weld pool behaviour in combination with shadow welding.

3.1.3. Line focus

A diode laser supplied with a line focus can melt the total length (8.8 mm) of the seam without movement of the beam or workpieces, this could prevent the displacement of material as was observed with the pulsed mode laser beam welding and shadow welding. The tests were performed with physical copper limits on the sides of the workpieces. The experiments were performed on Ultrafort material in a bead-on-plate configuration. It was the influence of the vertical copper limits that was of interest, if these limits could show the same influence as with the pulsed mode experiments, it could generate a fully penetrated seam without a lack of material at the sides of the workpieces as no significant movement of material is expected in the length direction of the seam.
In figures 103 to 106 the results were shown for a fully penetrated seam. There was only little oxidation present on the seam. A full contraction of the liquid weld pool over total width of the seam appeared; the vertical copper limits did not make it possible to prevent the contraction while having a fully penetrated seam over the total length. The parameters for these samples are shown in table 15.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Power [W]</th>
<th>Pulse time [ms]</th>
<th>Heat input [J/m]</th>
<th>Heat intensity [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B19, BOP</td>
<td>1500</td>
<td>250</td>
<td>$26.8 \times 10^3$</td>
<td>$1.8 \times 10^8$</td>
</tr>
<tr>
<td>B20, BOP</td>
<td>1500</td>
<td>300</td>
<td>$32.1 \times 10^3$</td>
<td>$1.8 \times 10^6$</td>
</tr>
<tr>
<td>B35, BOP</td>
<td>500</td>
<td>1100</td>
<td>$39.3 \times 10^3$</td>
<td>$6.0 \times 10^7$</td>
</tr>
</tbody>
</table>

Figure 103: Topside of sample B20 (P=1500 W, t=0.3 s)
Figure 104: Underside of sample B20 (P=1500 W, t=0.3 s)
Figure 105: Topside of sample B35 (P=550 W, t=1.1 s)
Figure 106: Underside of sample B35 (P=550 W, t=1.1 s)

The contraction of the weld pool showed a surprising phenomenon. The contraction did not always go in one step, but also in two or even in three steps (sample B35 first contracted to half the seam length and in second instance to the final dimensions). This step-wise contraction was observed with seams made with low power and long welding times (samples B35 and B36). The irregularity in figures 105 and 106 is probably the left over of the contraction in two steps.

The seam of sample B19 is not fully penetrated (see figures 107 and 108), it shows no oxidation and the weld pool in the middle has a width of 2.3 mm, the topside was melted over the full length of the seam. On the underside full penetration was not achieved at the sides of the workpieces. This sample did show a surprising
defect in the middle of the seam, a significant decrease in thickness was found. The size of the defect was measured with white light interferometry see figure 109. The X-profile is the height profile over the topside of the seam, it shows a defect of 60 µm. This seam quality is unacceptable.

Figure 107: Topside of sample B19 (P= 1500 W, t=0.25s)

Figure 108: Underside of sample B19 (P= 1500 W, t=0.25s)

Figure 109: Overview of the surface dimensions of the middle of the seam (B19, BOP, P= 1500 W, t=0.25s), a lack of material is found in the middle of the seam with a depth of about 60 µm, the material moved to the outside where the level is higher by about 10 µm.

3.1.4. Continuous wave laser beam welding

The first indications of the continuous wave laser beam welding process set the expectation that there will be a challenge to reduce the defect at the run-on and run-off see section 1.3. The results are discussed in five sections due to the five
different experimental welding arrangements that were tested, firstly the plain butt weld is discussed, secondly the influence of the vertical physical copper limit is considered followed by the influence of a maraging steel strip on the run-off, the influence of a maraging steel strip on the run-on and lastly the influence of different focus spot diameters.

3.1.4.1. Welding with a plain butt weld arrangement

The first welding arrangement tested was a seam welded from run-on to the run-off, with merely the aim to indicate the challenges that were faced. A smooth seam with a defect on the run-on and on the run-off was expected. The tests were done on Ultrafort material. The width of the seam and the size of the defect were expected to depend on the size of the focus spot, the influence of the size of the focus spot on the seam quality is discussed later in this section.

A butt weld with a continuous laser beam gave the results shown in figure 110 and 111 for the run-on and the run-off. The top of the seam had an irregular surface. The run-on showed a defect depth of 60-70 μm with a focus spot diameter of 225 μm. The defect depth on the run-off was 150-160 μm with a focus spot diameter of 112.5 μm.

![Defect](image1.png)  
**Figure 110:** Run-on of a butt weld seam (D49) welded with a continuous mode laser with spot size diameter of 225 μm (P=275 W decreasing linearly to 250 W at the end of the seam, v=33 mm/s, diameter focus spot=225 μm).

![Defect](image2.png)  
**Figure 111:** Run-off of a BOP seam (D36) with a continuous mode laser with a spot size diameter of 112.5 μm (P=200 W decreasing linearly to 175 W at the end of the seam, v=33 mm/s diameter focus spot=112.5 μm).

3.1.4.2. Welding with vertical physical copper limits

The presence of the defects on the sides of the seam is an inherent problem. One of the experimental arrangements designed to prevent the defects on the facet of the workpieces was the use of vertical physical copper limits. This was proven partial successful for pulsed mode laser beam welding. With this arrangement it was expected that the seam could be extended over the full length.

This experiment was done with the continuous laser with a focus spot diameter of 112.5 μm on Ultrafort. The seam had again a relatively irregular surface
quality. The run-on showed a flat surface in figure 112. The run-off is shown in figures 113, the run-off had a flat end in line with the facet of the strips, if the sample is compared with figure 111, the difference in the shape of the run-off can be ascribed to the influence of the physical copper limit. The surface near the edge still contained a defect, the seam decreases in thickness near the end and a net lack of material at the run-off is revealed. This decrease is measured with white light interferometry and was 90-100 μm. This net lack of material is in such an order that the arrangement does not show potential for further improvement.

![Figure 112: Run-on with copper limit, no defect is present in thickness and not on the edge (D31, P=200 W decreasing linearly to 175 W at the end of the seam, v=33 mm/s, diameter focus spot is 112.5 μm).](image1)

![Figure 113: Seam with Cu run-off tab, (D31, P=200 W decreasing linearly to 175 W at the end of the seam, v=33 mm/s, diameter focus spot is 112.5 μm).](image2)

3.1.4.3. Welding with run-on and run-off tabs

To improve the run-off of the seam the idea was to place a run-off tab from the same material at the end of the seam. The fluid flow in the weld pool could be continuous as the material would show only limited irregularities between the different strips. The run-on and run-off tabs would be easily separated after welding as the only connection was over the width of the seam.

First the influence of the run-off tab is discussed. The run-off tab had the advantage over the copper limit that it was the same material. This has the consequences that due to the fluid flow in the weld pool the seam is more continuous. Figure 114 shows an intersection of the workpiece at the run-off tab. The welding direction in this photo is from right to the left. At the right side of the picture a slight undercut is present. This is due to the curved edges of the workpieces. The distance between the flat top surfaces of the material is about 300 μm.
To prevent the creation of holes and obtain more stable results with the experiments done with Ultrafort material, the edges of the strips were ground to a straight edge. This reduced the distance between the topsides of the workpieces. In figure 115 both the edges were flattened and in figure 116 the edge of the run-out piece was also ground flat. The distance between the tcp surfaces of the workpieces were about 65 µm and in figure 116 about 175 µm. The results for both edge shapes gave stable reproducible results, no holes appeared and no undercut was created. An advantage of only one ground edge is that this fulfils the later facet requirements of the ring for the transmission push-belt.

Tests were also made to examine whether the geometry of the seam at the run-on could be improved with a tab. About the same results are expected as with the run-off, as the influence of the small gap between the workpieces and the influence of the welding direction are difficult to predict. The run-on without any run-on tab showed a defect of 60-70 µm, see figure 110. To improve this, the use of a
run-on tab was tested, this proved to be successful see figure 117 and 118. In figure 117 the edges were not ground, and in figure 118 the edges of the run-on tab were ground. The seam showed no undercut, and little oxidation was present. The surface was quite irregular, relatively large ripples were present in the weld pool.

![Image](image1)

**Figure 117:** Run-on with both edges un-ground (D50, P=275W decreasing linearly to 250 W at the end of the seam, v=33 mm/s, diameter focus spot is 225 μm).

![Image](image2)

**Figure 118:** Run-on with the run-on tab ground (D52, P=275 W decreasing linearly to 250 W at the end of the seam, v=33 mm/s, diameter focus spot is 225 μm).

For Phytim the setup with run-on and run-off tabs was also examined as shown in figures 119 and 120. It was difficult to obtain a full penetration with high welding speeds, but not impossible.

![Image](image3)

**Figure 119:** Topside of sample D110, welded with a 600 μm fibre, on the run-off an irregularity is present and an hole appears, (P=720 W decreasing linear to 550 W at the end of the seam, v=33 mm/s, focus spot diameter is 450 μm).

![Image](image4)

**Figure 120:** Underside of sample D110, the weld is fully penetrated (P=720 W decreasing linear to 550 W at the end of the seam, v=33 mm/s, focus spot diameter is 450 μm).

Bead-on-plate tests showed a parameter window for Phytim where it was possible to have a fully penetrated weld without creating a series of holes over the seam. It was shown that stable results could be obtained with relatively low welding velocities and low power. The only fully penetrated seam with a high welding velocity for Phytim was sample D110 shown above. These parameters were repeated and
did not give similar results, a series of holes was created. The parameter window is shown in figure 125.

![Graph showing welding velocity vs power](image)

**Figure 121:** Parameter window for the power vs velocity, the stable reproducible results are found in the lower welding velocity/power region.

### 3.1.4.4. Multiple ring welding arrangement

The last experimental welding arrangement tested was welding a series of workpieces adjacent to each other, described as multiple ring welding in section 2.2. This gave comparable results with the welding arrangement of welding with run-on and run-off tabs and is shown in figures 121 to 124. With low welding velocities (5 mm/s) it was possible to attain acceptable reproducible results.

![Multiple ring welding arrangement](image)

**Figure 122:** Topside of sample R24, laser joint made with 600 μm fibre (P=300 W, v= 5 mm/s, focus spot diameter is 450 μm).

**Figure 123:** Underside of sample R24, laser joint made with 600 μm fibre (P=300 W, v=5 mm/s, focus spot diameter is 450 μm).
**Figure 124:** Run-on of sample R24 (P=300 W, v=5 mm/s, 450 µm focus spot diameter, 15° leading)

**Figure 125:** Run-off of sample R24 (P=300 W, v=5 mm/s, 450 µm focus spot diameter, 15° leading)

Title: Veeco

Note:

**Figure 126:** Surface geometry of the middle of a Phytome welded sample with a 450 µm focus spot, v= 5 mm/s, P =300 W and 15° leading.

With the white light interferometry the surface topography is shown of sample R24, see figure 126. In the X-profile the surface showed sharp contours at the side of the weld bead. With further parameter optimization more improvement could be obtained.

**3.1.4.5. Influence of the focus spot size on the surface quality**

Examples of the 112.5 µm diameter focus spot (150 µm fibre) are shown in figures 127 and 128, the seam showed spatter droplets on the top and the underside with rough pattern of ripples on the topside. Examples of the 225 µm diameter focus
spot (300 µm fibre) are shown in figures 129 and 130, the amount of spatter droplets was reduced significantly, but still some spatter droplets were present, the ripples on the top surface were finer than with the 112.5 µm diameter focus spot. Examples of the 450 µm focus spot (600 µm fibre) are shown in figures 131 and 132. The welds made with a focus spot of 450 µm diameter gave the best results, the surface gave the smoothest appearance and no spatter droplets were present. This seam quality is acceptable. The widths of the different seams are listed in table 16.

Figure 127: Topside of seam with 112.5 µm focus spot (150 µm fibre, D46, P=200 W decreasing linear to 175 W at the end of the seam, v=33 mm/s).

Figure 128: Underside of seam with 112.5 µm focus spot (150 µm fibre, D46, P=200 W decreasing linear to 175 W at the end of the seam, v=33 mm/s).

Figure 129: Topside of seam with 225 µm focus spot (300 µm fibre, D52, P=275 W decreasing linear to 250 W at the end of the seam, v=33 mm/s).

Figure 130: Underside of seam with 225 µm focus spot (300 µm fibre, D52, P=275 W decreasing linear to 250 W at the end of the seam, v=33 mm/s).
Figure 131: Ultrafort sample welded with a 450 μm focus spot diameter (600 μm fibre, D75, P=650 W decreasing linear to 600 W at the end of the seam, v=33 mm/s).

Figure 132: Underside of Ultrafort sample D75 welded with a 450 μm focus spot diameter (600 μm fibre, P=650 W decreasing linear to 600 W at the end of the seam, v=33 mm/s).

Table 16: Width of seams made with different fibres with Ultrafort.

<table>
<thead>
<tr>
<th>Focus spot diameter [μm]</th>
<th>Diameter fibre [μm]</th>
<th>Seam width top side [μm]</th>
<th>Seam width underside [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>112.5</td>
<td>150</td>
<td>557</td>
<td>353</td>
</tr>
<tr>
<td>225</td>
<td>300</td>
<td>735</td>
<td>523</td>
</tr>
<tr>
<td>450</td>
<td>600</td>
<td>845</td>
<td>552</td>
</tr>
</tbody>
</table>
3.2. Electron beam welding

Electron beam welding is known to be able to produce seams with a high depth over width ratio. From these experiments an indication was expected of what would be possible with electron beam welding, whether the results are comparable to laser beam welding or perhaps much better results could be achieved.

The experiments of electron beam welding were done by the ISF RWTH Aachen. The experiments were performed on Ultrafort material under vacuum, no oxidation was present on the seam. The photos of the topside and underside of the seam are shown in figures 133 and 134. These show that the seam was fully penetrated. However the seam was not welded over the full length; the edges of the seam were not melted. The seam did not contract on the start and end of the seam. The strips showed some misalignment at the sides. The weld bead was surprisingly large, the width of the weld pool in the middle was about 2 mm. The parameters provided were: \( v_{\text{welding}} = 3.9 \, \text{mm/s}, \, I=1.2\, \text{mA} \) and \( U_{\text{acceleration \, voltage}} = 120 \, \text{kV} \). The current had a downslope as shown in figure 135. The given parameters are somewhat surprising as the width of the Ultrafort strip was 8.8 mm and the parameters show a travelling distance of the electron beam for 9 mm, while the material at the sides of the seam was not melted.

![Figure 133: Topside of electron beam welded seam (EB7), weld pool was not created over the full width of the seam.](image133)

![Figure 134: Underside of electron beam welded seam (EB7), not fully penetrated at the side.](image134)

![Figure 135: Current slope during electron beam welding with an acceleration voltage of 120 kV](image135)
When the seam was fully penetrated at the side of the material, the fluid weld pool contracted as shown in figure 136 for a large weld. Sample EB1 was a bead-on-plate weld, the parameters were not given.

![Figure 136: Run-off from an electron beam weld (EB1) that was fully penetrated at the side, a large defect appeared indicating on a large weld pool.](image)

The geometry of the seam is one important parameter to compare the different welding processes. The surface geometry in the middle of the seam is shown with white light interferometry in figure 137, the height differences are about 45 \( \mu \text{m} \). This is more than was expected. Only few experiments were done with electron beam welding, this makes it difficult to show the influence of the different parameters.
Figure 137: Surface depth profile of an electron beam welded seam, the profile is at the middle of the seam on the topside, it can be seen that the depth in the fusion zone is 45 µm.

Neither oxidation nor large irregularities were found on the weld pool. Due to the lack of information of the different parameters (exact circular deviation of the beam) not much can be said about the expected improvements with further experiments. No welds were made with run-on and run-off tabs; however with this experimental arrangement it is expected that better results could be obtained. The results are not expected to be of a different quality to the laser beam welding experiments as these processes can deliver about the same energy densities. Both are expected to make a seam with a good surface quality and no defects. The challenges for the run-on and run-off seem to be equal. The electron beam welding has the extra limitation that for a seam with a small width, the process should be performed under vacuum.
3.3. Plasma arc welding

The plasma arc welding experiments were done to show whether it was feasible to weld several rings positioned in line with each other using plasma arc welding as described under multiple ring welding in section 2.2. It is known that Phytime is weldable with the plasma arc process. The aim of these experiments will be to study the behaviour of the weld pool at the run-on and run-off region.

With this arrangement a seam was made over six strips, the seam was started on the intersection of the first two and ended on the intersection of the last two, the strips in the middle were welded over their full width. It was expected that the weld pool would show a continuous flow around the intersections if the strips are placed close to each other with no gap. The sensitivity of the formation of a hole in the seam due to a gap is not known.

The weld was made with; I=8.0 A, v_welding=0.8 mm/s, plasma gas flow=0.3 l/min and the torch was angled, 10° leading position. An overview of the middle strips of the seam is shown in figures 138 and 139.

![Figure 138: Topside of plasma seam (P1), a seam was made over the intersection of 6 strips (Current= 8.0 A, v= 0.8 mm/s).](image)

![Figure 139: Underside of plasma seam (P1), the blue parts on top of the seam are oxidized products.](image)

The surfaces of the rings show some oxidation products but these do not seem to have a detrimental influence on the geometry of the weld pool. The weld pool was 1.3 mm wide and showed no cracks. These results show that even the arrangement of multiple ring welding will be feasible with plasma arc welding. The run-on and run-off are shown in figures 140 and 141, by visual inspection no defects were found. It did show a small gap between the metal strips. The surface quality is measured with white light interferometry and the results are shown in figure 142.
Figure 140: Run-on for plasma arc welded sample P1, no defect in thickness is present.

Figure 141: Run-off of plasma arc welded sample P1, no defect is present in the thickness.

Figure 142: Overview of the seam geometry on the middle of the seam, the X-profile shows that the misalignment between the strips was 12 μm, the Y-profile shows height changes over the seam of about 12 μm, this is what is recognized in the macro photos as irregular.

Plasma arc welding with multiple rings was shown to be feasible. The surface geometry showed some irregularities but with good positioning of the thin strips, the intersection of the strips did not give a hole in the seam. The experiments were not done with the same parameters as the current production process. If the results are compared with a seam from the production process, more improvement on the surface quality can be expected. The influence of the shape of the facets of the thin
strip material was not further tested. The strips used in this process were cut but not specially shaped.

3.4. Upset welding

Upset welding is a solid state welding process, which means no melting takes place. The heating is done by electrical resistance and after heating the workpieces are pressed together, this forms an upset. From this process it is expected that around the seam an excess rather than a lack of material is present. Due to the heating near the interface of the workpieces, deformation is expected near the seam.

Experiments with upset welding were done by Strecker and Bihler with Ultrafort. Due to the differences in results, the characteristic results are shown separately. The process parameters from Strecker were not provided, from Bihler the process parameters were given as well as the design of the clamping setup.

The geometry of the seam produced by Strecker is shown in figures 143, 144 and 145. The upset was present around the total seam and had an irregular geometry. The alignment from the workpieces can be seen in figure 145, this figure also shows that there were no irregularities, scratches or porosity present in the seam. The width of the deformed zone from the upset was about 300 µm, the height of the upset was in the order of 1.75 to 2 mm.

Figure 143: Top surface of the seam (S7), irregular shape of the flash, also upset present on the sides of the strips.

Figure 144: Side view of sample S7, the upset is almost 2 mm.

Figure 145: Sample S7 embedded, the cross section shows the alignment and height of the upset.
The geometry of the seam from the samples from Bihler were the same as the samples from Strecker and the flash butt welded sample from Ideal. The samples had an irregular upset. For five of the samples the upset was removed with a grinding process and for the five remaining samples the upset was retained. In comparison to the upset of Strecker the upset was more regular as is shown in figure 146. Figure 147 shows that the misalignment of the strips was about 25 μm. The width where an upset was created was 250 to 275 μm.

![Figure 146: Sample Bihler 3, top view the upset, no large bulges or irregularities are present within the flash.](image1)

![Figure 147: The width of the upset was around 250 μm and the misalignment was 25 μm (sample Bihler 2).](image2)

For upset welding a joint can be created that contains no irregularities in the seam, these are all pushed out of the seam. The geometry of the upset will be dependant on the time a force is applied, the temperature developed in the material and the clamping device of the workpieces. It is not expected that the geometrical results will be significantly different for other materials such as Durimph or Phytime. The height of the upset does not really matter for the quality of the seam once all the irregularities are pushed out of the seam. The influences of the surface quality from the interfaces of the workpieces on the welding process were not tested.

### 3.5. Flash welding

The significant difference between upset welding and flash welding is the way of heating, with flash welding this is done by creating an arc between the workpieces and melting the surface material at the interface of the workpieces. After melting the workpieces are pressed together. This melting brings more heat into the material and as a result different metallurgy and mechanical properties are expected.

Experiments with flash welding were done by Ideal-Werk in Lippstadt, Germany, the process parameters were not given. From one of these samples the flash was removed by Ideal, this was done with a grinding process (not shown). The other two were received with a flash around the total seam. Figures 148 and 149 show the presence of the flash around the seam, the deformed zone is different for the topside and the underside see figure 150, this could probably be improved with a different clamping device.
Figure 148: Flash present on the up and underside of the seam (I1), height is about 650 μm varying over the seam up to about 2000 μm, the width of the deformed weld zone is 780 μm.

Figure 149: Flash present on the side of the seam (I1), an flash is measured of 438 μm on the side.

Figure 150: Sample I2 embedded, the asymmetric deformation is shown, no scratches or porosity present.

The geometry shows no significant differences between the upset welding and flash welding in these experiments. The largest differences are within the size of the upset and flash, these parameters were not optimized yet. The flash and upset will need to be removed in a later stage, a mechanical post-treatment is necessary. This will bring the joint to its final geometry and will be an important factor in determining whether this joining method can meet all the criteria.

3.6. "Mash resistance welding"

Mash resistance welding is a combination of resistance spot welding and mash seam welding where a resistance lap joint is deformed in such a way that a relative flat result is created. The amount of deformation is not clear and the deformation behaviour on the sides is also of great interest.

In figures 151 and 152 two samples of the "mash resistance weld" are shown. In this figure 151, the seam was extra deformed and also on the facet of the seam the material was deformed and a bulge was formed of 200-250 μm. In figure 152 the
sample was not extra force was applied and the burrs were not removed before welding, these were pressed in the material. The seams did not show any oxidation.

Figure 151: "Mash resistance weld" with extra deformation, forming a bulge on the side of the material.

Figure 152: "Mash resistance weld without extra deformation, the thin strips were not deburred.

The thickness of the seam could best be measured with white light interferometry. The measurement method shows the height profile of the seam. The influence of the extra deformation force and the surface topography is shown. In figure 153 the surface of sample M3 is shown, this sample was not extra deformed. The Y-profile shows the difference in height for the strips is still 70 μm. The other heights are listed in table 17. For these samples it is surprising that the defect height did not decrease with a higher deformation force.

Table 17: Defect height with different deformation forces for "mash resistance welding"

<table>
<thead>
<tr>
<th>Sample</th>
<th>Deformation force [$10^3$ kg]</th>
<th>Defect height [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>18</td>
<td>34</td>
</tr>
<tr>
<td>M2</td>
<td>12</td>
<td>29</td>
</tr>
<tr>
<td>M3</td>
<td>0</td>
<td>70</td>
</tr>
</tbody>
</table>
Figure 153: White light interferometry measurement over the mash resistance weld without extra deformation M3
3.7. Materials

Three different materials were used during this study, Ultrafort, Durimphy and Phyttime. These materials were subjected to different welding processes and different welding arrangements, an overview is given in table 12. The influence of the welding processes and arrangements are described for the different materials in section 3.7. As not all the materials were used with all the different arrangements a full comparison cannot be made.

3.7.1. Ultrafort

The first material for discussion is the cobalt-free maraging steel, Ultrafort. Ultrafort was used for widest variation of experiments including; pulsed mode laser beam welding, shadow welding, welding with a line focused laser beam, continuous wave laser beam welding, electron beam welding, upset welding and flash welding. The effects on the Ultrafort of the different methods of energy input into the material are discussed below.

The Ultrafort base metal consists of martensite, this is shown in figure 154, where a picture is shown of the metal etched with Adler’s reagent. The orange particles are TiN inclusions, the rest is martensite. Due to different orientations of the grains, locally different electrical potentials exist and the lath type of martensite is chemically attacked at different rates. The hardness of the parent material in the delivered condition is 345 +/- 10 HV0.5.

![TiN-inclusions](image)

Figure 154: Microstructure of the base metal of Ultrafort 1.6908 etched with Adler’s reagent, the orange inclusions are TiN.

The first welding experiment discussed is welding with the pulsed mode laser beam welding, which had a discontinuous heat input. The pulses were overlapped...
and the weld pool was for this reason also discontinuous. The pulsed mode laser beam welding showed a fully penetrated seam. Some pores were present as can be seen in the pictures in figures 155 and 156 (sample A27, Ultrafort, P=600 W, Fz=60 Hz, t\textsubscript{pulse}=4 ms, v\textsubscript{weld}=13.3 mm/s). The microstructures were revealed with Fry's etching reagent. Fry's reagent etches the martensite in the same manner as Adler's reagent, due to different grain orientations, the grains are attacked in a different way. The bands show the sides of the weld pool (i.e., the fusion boundary), these show the overlap of the pulses, and the local remelting of material in the fusion zone.

![Figure 155: Transverse section of a pulsed mode weld A27, Ultrafort is etched with Fry's reagent.](image1)

![Figure 156: Top of the transverse section of the seam A27, two pores are visible, and the fusion boundaries of the overlapping pulses are recognized by two dark bands.](image2)

The microstructure after annealing, etched with Marble's reagent is shown in figure 157. This etches martensite dark, again the martensite material seems totally attacked, less differences could be found ascribed to different orientations compared with Adler's or Fry's reagents where still lighter and darker areas are present. In figure 158 the hardness profiles through the weld are shown before and after annealing; a little local hardening is shown in the heat affected zone, at about 1 mm from the centre of the weld pool. This hardening is not present anymore after annealing for 15 minutes at 815°C.
Figure 157: Microstructure of sample A53 (P=704 W, v=13.3 mm/s, F=72 Hz and \( t_{\text{pulse}}=2.5 \text{ ms} \)) after annealing, the structure is fully recrystallized and this gives a more homogeneous structure.

From the pulsed mode welding experiments it was seen that the Ultrafort material showed only small microstructural changes over the weld pool and the heat affected zone. The experiments with the line focus had a higher energy input and transverse cross-sections are shown in figures 159 and 160 indicating the results from the centre of the weld pool after welding. Figure 159 shows some porous like cracks near the surface in the centre of the seam. In figure 160 the transverse cross-section was etched with Fry’s reagent and a homogeneous structure was found in the centre of the weld pool.

Figure 158: Hardness profile over the pulsed mode welded seam, purple profile is the hardness profile directly after welding, relatively flat, the blue profile shows the hardness after annealing.

Figure 159: Transverse cross-section of the centre of the seam made with a line-focus, on Ultrafort, unetched

Figure 160: Transverse cross-section centre of a part of the weld pool made with a line focus, etched with Fry’s reagent

The best results for the surface geometry with a continuous wave laser beam were achieved with a focus spot of 450 \( \mu \text{m} \) diameter. The results with Ultrafort are shown in figures 161 and 162. The seam was fully penetrated, and had a flat top surface; the seam only showed one pore in the cross-section. The dark etched spot at the side of the material is enlarged in figure 162. These show a dense concentration of spherical particles that form a dark zone.
Figure 161: Sample D70, cw laser beam welded, fully penetrated, one pore visible. The etchant was Fry’s reagent.

Figure 162: Dark etched area of the weld pool, the fusion boundaries show similar less dense dark spots that form a band.

The heat affected zone is shown in figure 163. No significantly different morphologies appeared with continuous laser beam welding. The hardness over the seam does not increase significantly, the purple squares in figure 164 are before annealing and the blue diamonds show the hardness profile after annealing.

Figure 163: Overview of the weld pool, only a small heat affected zone is present etched with Fry’s reagent.

Figure 164: Hardness profile over the seam, before (purple) and after annealing (blue).
A different welding process used for Ultrafort was electron beam welding, the weld pool was compared to the laser beam welding experiments, which indicates a larger heat input. In figure 166 a sketch is made to show the locations of the different morphologies in the electron beam weld. The microstructure is shown in figure 167 to 170, sample EB7 was etched with Kalling's etching reagent. From the literature it appears that Kalling's etching reagent etches the martensite dark, austenite is slightly attacked and ferrite is coloured [32], the result that was observed showed a similar result to Adler's reagent. In the heat affected zone of the electron beam weld different zones appear. Light differences in morphology are shown at different distances from the weld pool. The first morphology next to the weld zone is shown in figure 167. The martensite showed vague boundaries and showed no sharp contrast.

Figure 166: Overview of the locations for the different morphologies observed in electron beam welded Ultrafort.
The zone that is located next to this zone shows characteristic sharp dark edges around the martensite see figure 169. The next zone shows dark etched grains and not only the edges of the martensite strips are darkly etched but also the total grains see figure 170. After this zone the morphology of the base metal starts again.

The hardness is shown in figure 171, the joint shows a small increase in hardness over the seam, this is only a small increase and is typical for the Ultrafort material and not so much for the heat input of the electron beam welding process performed in these experiments.
Next to the fusion welding processes two resistance welding processes were performed on Ultrafort; upset welding and flash welding. Upset welding was performed by two companies Strecker and Bihler, these showed different results. First the results from Strecker are presented.

Sample S6 is shown in figure 172, this shows representative results for the Strecker experiments. Figure 173 shows that no cracks, pores and other irregularities are present in the seam, there is only a misalignment of the two strips. When etched, it can be seen that the hardened layer on top of the Ultrafort is still present; this indicates that the material was not melted, a deformed structure was not present. In figure 174 a sketch is made to show the locations of the different morphologies in the upset weld. The weld zone structure is shown in figure 175.

Figure 172: Unetched seam S6 shows, no irregularities nor cracks, only a misalignment between the strips.

Figure 173: Sample S6 etched with Adler's reagent, no deformed structure is seen, but a full recrystallized structure is obtained.
The heat affected zone showed similar morphologies to the electron beam welds. In figures 176 to 179 the morphologies are shown in detail. The first morphology shows dark boundaries around prior austenite grains, within these cells martensite is present (figure 176). The second morphology shows a lighter etched zone (figure 177), comparable to the structure in figure 178. Thirdly a zone with sharp, dark boundaries around the martensite laths see figure 178, and lastly a more uniformed attacked zone with less contrast see figure 179. Next to this zone the base metal starts again.
The hardness showed no specific pattern see figure 180, neither harder zones nor softer zones could be distinguished this was surprising as several different zones were present over the joint.

A second series of upset welding experiments were done by Bihler. No differences with the experiments done by Strecker were expected. These experiments were nonetheless significantly different.

In figures 181 and 182 the microstructures from the middle of the seam are shown. The microstructure at the seam is a deformed structure. No signs of a melted zone or a recrystallized zone are present. No distinguishable morphologies were found outside the deformed zone.
The micro-hardness tests did not give any clear signs of strengthening taking place over the seam see figure 183. This is a surprise while the microstructure does show a lot of deformation. If the seam is annealed, the structure is recrystallized and the material shows a homogeneous structure, see figure 184. The hardness after annealing was a bit more homogenized.

![Hardness profile](image)

**Figure 183:** Hardness over the upset welded seam, purple profile shows the hardness before annealing, blue profile shows the hardness after annealing, the hardening is not significant.

The second resistance welding process was flash welding, a characteristic of this process is the melting that takes place. The molten metal is pushed out by a pressure and after solidification a joint is made.

This process also showed surprising results. Figure 185 shows an unetched seam, on the top side is a large deformation of the surface, this is probably due to the electrodes that did not have the most optimal shape. No pores or cracks were present in the seam. Typical microstructures for the weld zone are shown in figures 186 and 188 these were etched with Adler’s reagent. There the structure shows in the middle signs of deformation. If the amount of flash is analysed it shows a significant volume of material, this was most likely more material than was expected.
to be molten during flashing and suggests that after the molten material was pushed out of the seam, a significant amount of deformation also took place.

The hardness after welding was measured and is shown in figure 187, no significant hardening effects were found in and around the seam. The deformed structure showed no hardening, in common with the previous results for upset welding.

Figure 185: Overview of unetched seam, no porosity or cracks present, large deformation present on the top.

Figure 186: Overview of the weld zone, etched with Adler's reagent, two separate bands still seam present.

Figure 187: Hardness profile over the seam, like the results with upset welding. No hardening effects due to the heat input and deformation are present in the Ultrafort material.

Figure 188: Weld zone, no molten structure is visible.
3.7.2. Durimphy

The second material used in this project is Durimphy. This 18% Ni maraging steel was examined with different welding arrangements; both sides of the strips were welded with shadow welding, and continuous wave laser beam welding with a run-on and run-off tabs. These can be compared with the samples from the welding process currently used for the production of the transmission push-belts.

The Durimphy is pure martensitic steel and was welded in the annealed condition. A sample of the base metal is shown in figure 189 this sample is etched with Fry's reagent. It shows the sharp angled grains of lath type of martensite. The hardness of the parent material in the delivered condition is 331 +/- 11 HV0.5.

![Fully martensite](image.png)

Figure 189: Base metal of Durimphy etched with Fry's reagent.

The first welding arrangements where Durimphy was employed included: both sides of the workpieces being welded with shadow welding to give a full penetration weld, with only a little porosity, see figure 190. The experiments were done with flat physical copper limits at the run-on and run-off and the welding velocity was 280 mm/s. Sample L232 in figure 191 is etched with Fry's reagent and shows some pitting corrosion on the top and bottom surfaces. A radially oriented structure is observed from the two weld beads, the first seam is on the topside and the second on the underside. It shows that the seam is fully penetrated, as there is an overlap between both weld pools. No special phases were observed in the microstructure in and around the weld pool.
In the literature it is indicated that nital can etch the martensite in a satisfactory way for carbon steels [33], it is described that nital etches the ferrite boundaries and etches martensite with detail [32]. Physical copper limits were placed against the sides of the strips during welding. Figure 192 shows a longitudinal section of the seam, etched with 3% nital, copper was bonded to the seam, this observation will be important for the evaluation of the welding methodology.

In figures 193 and 194 the overlap (about 30 µm) of the two seams can be seen, this is the band in the middle of the strips. The influence of the first pulse (P=1200 W, depth of about 180 µm) and the second pulse (P=1400 W depth of about 230 µm) can be recognized with the higher penetration of the heat from the top side. In figure 194 the top layer is clearly melted and in the second pass the underside was welded.

The crystal growth is epitaxial and perpendicular to the copper surface, nital does not show the martensite as expected, it mainly reveals the prior austenite boundaries.
Figure 193: Sample L231 in the length of the seam embedded and etched with 3% nital. The solidification structure is clearly shown. A band of overlap is visible in the middle of the strips.

Figure 194: The overlap enlarged, the topside was welded first.

In figure 195 the microstructure of sample L228 is shown, this sample was etched with Marble's reagent and welded on both sides of the strips. Marble's reagent reveals the differently oriented martensite laths. After annealing (at 815°C for 15 minutes) the grains were more homogeneous but still it is possible to distinguish the fusion zones.

The hardness over the seam was measured from a sample before annealing and after annealing and is shown in figure 196. After welding and before annealing the hardening products were formed outside of the seam in the heat affected zone. After annealing no hardening was found. The width of the weld pool was ~500 µm and the location of the hardening was about 800 µm from the centre of the seam.

Figure 195: Fusion zone of the annealed structure (L228), the overlap of the two seams can still slightly be seen.

Figure 196: Hardness profile over the seam welded on both sides. The purple squares are form the hardness profile before annealing, the blue diamond profile is the hardness after welding.

Further experiments with continuous wave laser beam welding and Durimphy were done with a velocity of 13.3 mm/s and with Durimphy run-on and run-off tabs. The aim was to obtain a defect free fully penetrated seam.
This aim was successfully reached see figure 197. In this figure the cross-section is shown, the seam was etched with Fry's reagent. It is difficult to see the weld pool. On the top and the bottom some pitting corrosion is present, this was not present after welding only after embedding and etching. For the annealed sample, figure 198, the characterisation of the weld pool is even more difficult. From the underside it can be seen that the weld is fully penetrated and some misalignment was present between the different workpieces.

![Figure 197: Sample D81 etched with Fry's reagent, seam fully penetrated, some pitting present on the top and bottom.](image1)

![Figure 198: Sample D83, continuous laser beam welded seam fully penetrated, etched with Marble's reagent.](image2)

The hardness profile of the continuous laser beam weld is shown in figure 199. The general result is the same as that observed with the shadow welding, the hardening that took place during welding was in the heat affected zone and disappeared during annealing. The location of the hardening was outside the weld zone in the heat affected zone.

![Figure 199: Hardness profile over the seam, for continuous laser beam welding before annealing (purple, D87) and after annealing (blue, D83).](image3)

The results can be compared for Durimphy with the results of the plasma welding of the production process, before and after annealing. These are shown in figures 200 and 201. The dark etched zone was made visible with nital etching
reagent for the sample without annealing, again the nital only reveals the prior austenite boundaries and the precipitated hardened zone. For a sample that was plasma welded after annealing no dark etched zone was present (see figure 201).

![Figure 200: Right plasma arc weld of ring directly after welding, and the heat affected zone etched with nital 5%, the dark etched zone located at about 850 μm from the fusion boundary.](image1)

![Figure 201: Plasma arc weld and heat affected zone after welding, etched with nital 5%, the dark etched zone is not present.](image2)

The hardness profile is shown in figure 202, this shows again the hardening in the heat affected zone, after annealing this hardening was not significant anymore. The hardening peaks directly after welding showed an unexpected asymmetry, while a symmetric hardening profile was expected. The hardening behaviour was less than with the laser beam welding experiments, this was surprising as well, because the heat input was larger for the plasma welding experiments and more hardening was expected.

![Figure 202: Hardness profile for plasma welding, before annealing (purple) and after annealing (blue).](image3)
3.7.3. Phytime

Different experiments were undertaken with Phytime, but due to its limited availability not all of the experiments were performed with this material. It was the most interesting material for this study, as quality improvements could be made by its application to transmission push-belts. The experiments performed with Phytime were continuous laser beam welding with a run-on and run-off tabs, plasma arc welding with a run-on and run-off tabs and the "mash resistance welding".

The base metal is shown in figure 203, it was welded in a cold rolled condition. The hardness of the parent material is 385 +/- 13 HV0.5.

![Figure 203: Phytime in cold rolled condition, etched with Nital.](image)

The Phytime was welded in a cold rolled condition. For a continuous wave laser beam weld with run-on and run-off tabs, the weld pool could be fully penetrated. An overview of the seam is shown in figure 204, this was etched with Marble’s reagent, the width of the fusion zone is 1.3 mm, the width of the heat affected zone is 2.2-2.4 mm, where the dark etched zone is located at 1.2-1.4 mm.

![Figure 204: Overview of weldzone of R24, FZ=fusion zone, HAZ= heat affected zone (can be split in the dark-etched zone and a light etched zone) and BM= base metal.](image)

The microstructure of the seam is shown in figures 205 to 208, an overview of the heat affected zone is given in figure 204, in this figure the grains decrease in size moving from the weld pool towards the dark etched zone. The edge of the weld pool contained large grains, and the middle of the seam finer grains (see figure 207).
Figure 205: Heat affected zone from the continuous laser beam welding, etched with Marble's reagent.

Figure 206: Microstructure of the centre of the fusion zone of sample R24, etched with Marble's reagent.

Figure 207: Light etched zone, grains become smaller further away from the fusion zone, positioned left of this picture.

Figure 208: Dark etched zone, weld zone positioned left of this picture.

The hardness was significantly increased to over 500 HV0.5 in the heat affected zone, see figure 209. This is more then was observed with Durimphy. The hardening took place at about 2 mm from the centre of the weld pool, this was the location of the dark etched zone.
Plasma welding was performed with a run-on and a run-off tab. The metallurgy of the seam is quit similar to the laser beam welded sample as shown with sample R24 above. Figure 210 shows the weld pool etched with Nital, the pores are present due to pitting corrosion. Figure 211 shows the weld pool etched with Marble’s reagent, the centre shows a different solidification structure. The weld pool shows large grains on the side and further to the middle smaller grains were found.
The hardness profile of the plasma seam P1 is shown in figure 214, the hardness is increasing around the heat affected zone and increases in a similar way as was seen in the continuous wave laser beam weld (sample R24), to a hardness of over the 500 HV0.5. The local strengthening happens around the dark etched zone.

The last process employed with Phytime was “mash resistance welding”. For this process no parameters were available, the structure of a transverse cross-section is shown in figures 215 and 216. In this cross-section a weld nugget is seen, the nugget is quit common for resistance spot welding. The overlap of the two strips, are deformed but still a defect is present on both sides, the deformed interface between the two workpieces contain pores, no melting took place outside the nugget. The amount of bonding that took place outside the nugget is difficult to determine from these photographs.
Figure 215: M5, "mash resistance weld" etched with 5% Nital, centre shows the weld nugget.

Figure 216: M5, heat affected zone of "mash resistance weld", etched with 5% Nital.

The hardness formation around the seam is shown in figure 217, little hardening was found. The decrease in hardness in the middle of the seam is also found in the other welding experiments with Phytime.

Figure 217: Hardness profile over "mash resistance weld" with Phytime material.
4. Discussion

In this project different welding arrangements were tested for welding thin strip material to create a joint with only a low amount of geometrical and metallurgical defects. Different materials were used as shown in table 12 and often surprising phenomena took place, these will be discussed in the following sections. Again the chapter is split up into two parts, the first part where the welding processes and arrangements are discussed and the second part in which the different materials are discussed.

Various welding processes were used in this study, all of these welding processes had different influences on the geometry of the seam as they had different ways of applying energy into the material for creating a joint. Some of these phenomena could be predicted and some were unexpected, the characteristic results are discussed to create a better understanding for what has been observed and reported in chapter 3.

4.1. Laser beam welding

Four different laser beam welding processes were used, pulsed mode laser beam welding, shadow welding, laser beam welding with a line focus covering the total width of the seam and continuous wave laser beam welding. The influences of the different processes and welding arrangements used are discussed.

4.1.1. Pulsed mode laser beam welding

The first process, pulsed mode laser beam welding was only tested with Ultrafort and with two welding arrangements: the plain butt weld (most experiments were done bead-on-plate) and welding with copper limits. Characteristic results were the rippled seam and the dimensions of the seam, the presence of spatter on the underside, the differences between the run-on and run-off of the seam and the influence of the copper limits on the run-on and run-off. Some open questions remain after these experiments and these are addressed here.

The shape of the surface was shown in figure 52 and also measured in figure 54. The laser had a focus spot with a diameter of 300 μm. This gives an energy density with a power of $P=600$ W of $8.5\cdot10^9$ W/m$^2$, the welding mode is keyhole welding. A plasma was present during welding, which is an indication of significant vaporization, which occurs during keyhole formation.

The width of the weld pool on the top-side was 710-750 μm. The length of the weld pool was influenced by the welding velocity. During the pulse with a length of 4 ms the beam was moved with a velocity of 13.3 mm/s over a distance of 53 μm. The shape of the weld pool caused by a single pulse is expected to be elliptical on the top surface. The pulse cycle time for the two frequencies (60 Hz and 72 Hz) used are 16.7 ms and 13.9 ms. The solidification time is calculated with equation 16 [34]
\[ S_y = \frac{LH_{\text{net}}}{2\pi k \rho C(T_m - T_0)^2} \]  

\( L = \) Heat of fusion (for steels) = 2 J/mm\(^3\) = 2*10\(^9\) J/m\(^3\)  
\( H_{\text{net}} = \) Net heat input per unit length = 10.8 J/m  
\( k = \) Thermal conductivity = 19.7 W/K*\( m \)  
\( \rho = \) Density of the base metal = 8.0 \( 10^3 \) kg/m\(^3\)  
\( C = \) Specific heat of the base metal at 700 K = 8.6*10\(^{-2}\) cal/g*K = 362 J/kg*K  
\( T_m = \) Melting temperature = 1713 K  
\( T_0 = \) Initial plate temperature = 298 K

The calculated time amounts to 0.6 ms which indicates that the weld pool is discontinuous. A calculated value predicts a distance between the rear of the pulses of approximately 220 \( \mu \)m (distance = \( v_{\text{weld}} / F_z = v_{\text{weld}} t_{\text{cycle}} \), this is the distance travelled during 1 pulse cycle). The distance between the different pulses for sample A27 is 207 +/- 24 \( \mu \)m with \( F_z = 60 \) Hz, \( t_{\text{pulse}} = 4 \) ms and \( v_{\text{weld}} = 13.3 \) mm/s measured over 10 pulses. This value is below the calculated value, the difference could be related to errors in the pulse cycle time, the pulse time and/or the welding velocities. Data for the precision of these parameters was not available; however these unstable results between successive overlap need not be harmful for the seam quality.

For this welding process it would be interesting to have the results for the geometry after rolling, this could change the dimensions drastically. For plasma welding the differences in height over the seam (shown in figure 15) were levelled from a height difference of 31 \( \mu \)m to less than 1 \( \mu \)m if the ring is not tumbled. The height differences with pulsed mode laser welding are more irregular than the plasma weld. The influence of the rolling process is difficult to predict as the defects are not orientated in the rolling and deformation direction.

The thickness over the width of the pulses decreases. In the middle of the pulse this decrease was about 10 \( \mu \)m (see the Y-profile in figure 54). This could be due to two reasons, firstly the shrinking of the weld pool after solidification, the deformation takes place in the middle of the weld pool as the warmer material has a lower yield strength than cold material [35], and secondly the mode of welding was keyhole, after the pulse the keyhole closes due to surface tension and hydrostatic pressures [36, 37] and the refill of the keyhole could leave a net lack of material in the centre, the latter probably being the largest contributor to the thickness decrease.

The differences between the start and end are that the latter had a defect with a depth of 160 \( \mu \)m of material where the former only showed a defect of 30-40 \( \mu \)m (figures 55 and 56). A difference between the run-on and the run-off could be due to the material movement during welding. The run-off showed a larger defect than the run-on, hence a net flow seems to be present and is oriented in the opposite direction of the welding direction. No literature was found on material flow during pulsed mode laser beam welding, but if pulsed welding is considered the same as continuous laser beam weld with very low welding times the material displacement could be better
explained. From the literature it is known [38, 39] that a keyhole needs about 2 ms to form in steel sheets of 1.2 mm thickness, with a welding velocity of 25.4 mm/s and a power of 4 kW on a focus spot of 500 µm. It would be likely that the keyhole in our experiments with lower welding velocity, much smaller thickness but also somewhat lower power density would need the same order or less time to form the keyhole. The transport of fluid during continuous mode laser beam welding is discussed in the section on shadow welding (see page 109), as the effects are best observed with this process.

For the prevention of the contraction at the start and end of the welds copper limits were placed adjacent to the strip edges. This proved to be successful, see figures 59 to 64. The lack of material in the thickness was discussed above. For the reason of the prevention of the contraction of the seam two ideas were suggested in the experimental section. Firstly due to the wettability of the liquid material, the weld pool stayed attached to the physical copper limits because the surface free energy was lowered by the presence of the copper. The second suggestion was that the weld pool was quenched directly against the copper limit and that this prevented the weld pool from contracting.

The former would be possible if the total sum of the surface tension (in case of liquid gas contact) and surface free energy (in case of liquid-solid contact) is reduced when the weld pool is attached to the copper surface. The surface tension of the separate elements of maraging steel has been found, only the surface free energy between the different elements of maraging steel and copper have not been found. The lack of availability of these data could well be because the melting temperature of copper (1084 °C) is lower than the melting temperatures of iron, nickel, cobalt or maraging steel (resp. 1538 °C, 1453 °C, 1495 °C and ~1440 °C). The time for stable fluid flow is thus limited by the time it takes for the weld pool to solidify. Characteristics of the weld pool would be a smooth and an as small as possible surface. From figures 61 and 64 this does not seem to be the case, the flat surface had a roughly shaped outline.

The above implies that the second arrangement for the prevention of the contraction of the seam quenches the molten material immediately after the fluid metal touches the physical copper limit. From the surface geometry, the conclusion can be drawn that the weld pool is quenched by the copper.

The use of physical limits might be improved with a different material with different surface energy properties and with a higher melting temperature, for example tungsten, that has significantly different surface energy properties [40]. This improvement would not solve the phenomenon observed earlier with the lack of material at the run-off position. These arrangements were not explored further for this reason.

Some questions remain unanswered; for example, what would happen when Durimph or Phytime would be welded instead of Ultrafort? Would the creation of spatter be significantly different for these materials? This could occur due to different fluid properties of the different materials. Other effects like the net movement of material are not expected to be significantly different as this is an effect ascribed to
the welding velocity, power density and the viscosity of the molten metal. A second question is what the surface geometry would be after rolling of a pulsed mode welded seam? This would also be of influence for the feasibility of pulsed mode laser beam welding. A third question is what would the result be if maraging steel run-off tabs would be used? Would this give similar results as the continuous laser beam welding? In general pulsed mode laser beam welding does not seem the best solution for thin strip welding.

4.1.2. Shadow welding

The second welding process was tested with Ultrafort and Durimphy. With Ultrafort the following welding arrangements were tested; bead-on-plate (BOP) welding from side to side, welding with the laser beam moving in one direction (BOP), welding with the use of copper limits on the run-on and run-off (BOP), welding with two pulses in overlap in the middle (BOP) and welding while moving the laser beam in multiple directions (BOP). Welding on both sides of the strips was performed with Durimphy in a butt weld configuration.

For shadow welding the results that were obtained were not promising for welding the strip material with low levels of defects. Different factors were further evaluated to understand the difficulties encountered with shadow welding, these include the influence of the different welding parameters, the influence of the copper limits on the sides and the different ways of moving the beam over the work piece.

Two parameters that need to be considered are the welding velocity and the welding power. In general the defects became larger with increasing velocity, the power was adjusted in such a way that the weld pool fully penetrated the strips. The heat input is a combination of these two factors and is the amount of energy input per unit length. Table 18 shows the power, velocity, heat input and power density at the focus spot and the measured depth of defects at the run-off for the different experiments.

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>1500</td>
<td>200</td>
<td>1.2</td>
<td>7.5</td>
<td>0.8</td>
</tr>
<tr>
<td>2300</td>
<td>400</td>
<td>1.8</td>
<td>5.8</td>
<td>Not fully penetrated</td>
</tr>
<tr>
<td>4400</td>
<td>800</td>
<td>3.5</td>
<td>5.5</td>
<td>1.8</td>
</tr>
<tr>
<td>9500</td>
<td>1600</td>
<td>7.6</td>
<td>5.9</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Welding was done in keyhole mode, this is expected from the power density and could also be confirmed by the plasma present during all the welding experiments, which indicates that the vaporization temperature is reached in the centre of the weld pool.

For the highest welding power no weld was made but all of the material appeared to be blown away and the weld was not fully penetrated, see figures 68.
and 72. The reason for this phenomenon can be found in the high recoil pressure and the large vapour pressure. When the creation of the keyhole is studied in detail, it is formed by the recoil pressure exerted by the vaporizing particles and the keyhole is kept open by the vapour pressure in the weld pool. Forces closing the keyhole are the hydrostatic forces and the surface tension which exerts a pressure tending to reduce amount of surface area. If the recoil pressure and or the vapour pressure differ locally in large amounts, this could lead to instabilities in the shape of the keyhole, and if these pressures are much higher than the surface tension and the hydrostatic pressures, the liquid will be pushed away. The vapour pressure increases with the temperature, the recoil pressure increases with the square of the power density of the beam (see equation 12), the beam pressure increases linear with the power density (see equation 14). The compensating pressure is the surface tension which decreases with temperature. The second closing force is the hydrostatic force which decreases only slightly with temperature. All of these factors have a trend toward forming instabilities with higher energy densities.

With the lower three welding velocities a trend was observed; that more material was moved toward the run-on of the seam as the welding velocity was increased, and the defect at the run-off of the seam became larger. The weld pool behaviour is highly dynamic, various interesting experiments in following the shape of the weld pool have been performed [41, 42], and also various simulations of the weld pool during keyhole welding have been made [38, 39]. The different flow behaviour is not proven to be dependant on the welding velocity by the simulation of Mazumder. From his simulations the fluid flow increased with the power (and thus the energy density). These simulations were made for welding velocities between 25 mm/s and 42 mm/s. From experimental values, different fluid flow velocities came forward within this range of welding velocities, but no clear trend was observed. In the experiments done in this project it is likely that the fluid flow increased with higher welding velocities and higher energy densities, shown by the material movement towards the run-on (see figure 65 to 80). To give an indication of the flow in the keyhole the results of experiments of Matsunawa are shown; in this experiment a tungsten particle was followed with an X-ray photographic method [37]. This shows the complex flow behaviour in the weld pool (figure 218).
Figure 218: Fluid flow observed by X-ray method, \( v=25 \text{ mm/s} \) and \( P=10 \text{ kW} \) [37], numbers are the elapsed time (ms).

In figure 192 it was shown that an epitaxial grain growth occurred in the weld pool. This was most likely due to the influence of the cooling by the copper. The orientation of the grains is usually determined by the direction of the heat flow.

The physical limits had no visible influence on the run-off. The difference between the run-on and the run-off could be explained within the fluid dynamics described above; the material moved in the opposite direction of the welding direction. The fluid dynamics in the weld pool were apparently much larger than with the pulsed mode laser beam welding where the run-off kept in contact with copper limit.

The experiments with different paths made by the laser beam did not solve the geometrical challenges. Neither the two-step process nor the three-step process gave homogeneously distributed results. These had similar problems as discussed above with welding in one-step, the movement of material over the seam limited the possibilities with this welding arrangement.

A second challenge was faced during the welding arrangements with the two-step and three-step welding process with a full penetration which led to the creation of holes in the middle of the seam. These were created at the location where the beam passed for the second or third time. A reason for this phenomenon could be the discontinuity in the thickness of the seam due again to the displacement of the material in the weld pool. Due to the discontinuity no equilibrium for the heat input could be found with stable results, at the location of an overlap a hole was created. The exact cause for the creation of the hole is a difficult question. It is often observed when welds are produced with higher powers than needed. More details about material flow around the keyhole and in the weld pool are needed to explain the creation of holes in a weld due to irregularities.

The arrangement of shadow welding the strips on both sides of the material gave the best results, because the run-on and run-off were opposite on the different sides of the strips. The seam was fully penetrated after the two welding steps and there was material present over the total length of the seam. The distribution of material was not homogeneous. This had similar reasons as discussed in the first section.

Shadow welding had no positive results for welding thin strip material with low amounts of defects. The experiments did not have the proper material distribution. Material flow occurred to such an extent that shadow welding did not show any potential for further testing. Better results might be obtained with lower welding velocities and lower power densities.

4.1.3. Line focus

The results in the experiments with the line focus were shown in figures 103 to 109, the outcome was that the copper limits did not show a positive effect on the geometrical dimensions of the seam, when the seam was fully penetrated over the
total length, a contraction took place. The physical limits did not show a cooling or quenching effect as observed with the pulsed mode welding. No experiments were performed where the seam was fully penetrated and did not contract. The melting of the material was achieved by conduction of heat. The welding times were relatively long, the heat input and heat intensity are shown in table 15. The heat density was too low to create a keyhole, which suggests that the temperature of the weld pool in the middle of the seam did not reach the vaporization temperature.

In the seam the material flow could be compared to a conduction mode laser beam weld. If the laser beam intensity over the total width of the seam is constant the flow could be assumed to be two dimensional in the middle of the seam and is expected to be as schematically drawn in figure 219.

![Diagram](image)

**Figure 219:** Expected 2d-flow in laser beam welding with a line focus, an outward flow is expected due to the surface tension.

The cooling effect of the copper and the cover gas flow will influence the temperature profile, this would further influence the material flow. In this welding configuration the forces that are interacting within the weld pool are the beam pressure and the surface tension, causing Marangoni flow. Flow caused by the surface tension during welding was simulated [43], and resulted in an increase in thickness at the sides of a weld pool. This could explain the increase in thickness of the seam shown in figure 109. Other pressures like the beam pressure and the differences in buoyancy due to temperature differences influence the surface geometry but are not expected to be dominant.

The decrease in thickness of 50 μm in the middle of the seam could also be influenced by a different phenomenon. The shrinking of the material during and after solidification could play a significant part. As the weld pool was not fully penetrated on the facets of the seam and the weld was bead-on-plate there is a difference between the expansion of the material in the weld pool and on the facet of the workpieces. The material deforms most easily at the hottest part, which is the middle of the seam.

Simple calculations can be done if a few assumptions are made, the temperature of the weld pool and the facet of the strips differ by about 200 K (this is a rough estimation), the thermal expansion coefficient is taken as a constant for the
total temperature range \((\alpha=1.008\times10^{-5} \text{ K}^{-1} [44])\) and the expansion of the material can be calculated with equation 17 [45].

\[
\frac{\Delta l}{l_0} = \alpha \Delta T
\]

(17)

This would theoretically result in a difference in expansion between the middle and the side of the seam of only 4.6 \(\mu\)m (for a 2.3 mm wide seam). The calculated expansion does not need to result in deformation, as this will firstly form strains into the material and only secondly if the strains exceed the yield strength, cause deformation in the way that was observed. The cooling shrinkage does not seem to be the only factor in the decrease of thickness in the middle of the seam. Further mechanisms are not discussed as this process option is not considered suitable for the intended application.

**4.1.4. Continuous wave laser beam welding**

For continuous laser beam welding four different phenomena will be discussed; the difference of the geometry between the run-on and run-off of a butt weld, the influence of the copper limits on the run-on and run-off, the influence of maraging steel run-on and run-off tabs and the influence of the different focus spot size on the surface quality of the seam. These phenomena are of importance for the geometry of the seam.

The first phenomenon was the difference between the run-on and run-off of the seam. The run-off showed a larger defect in depth than the run-on (figures 110 and 111). The explanation for the defect at the run-on could be due to the surface tension that optimizes the amount of surface area of the liquid. This increases the thickness of the seam and results in a defect on the facet.

For the run-off these forces should also be present, but a larger defect is present than was observed at the run-on. This could well be formed by the keyhole that is expected to be present during this welding process. The energy density is shown for the optimal parameters (full penetration) in table 19. In combination with the presence of a plasma, these parameters are expected to be sufficient for the creation of a keyhole during welding. When this keyhole is at the run-off of the seam, the keyhole could leave a hole which corresponds approximately to the size of the focus spot. For sample D36 in figure 111 this should be a defect with a diameter of 112.5 \(\mu\)m, but the defect is as wide as the seam, this could again be due to the surface tension that reduces the surface area of the liquid weld pool to a minimum.

A third factor that could influence the different size of the defect at the run-on and run-off, is the different temperature distribution. The fluid flow in the weld pool is influenced by the temperature. As the run-on is cold when welded and the run-off is preheated by thermal conduction, the fluid flow could be significantly different and therefore the defect size could be influenced as well.
Table 19: Power density with the best parameters for the continuous laser beam experiments for the different fibres

<table>
<thead>
<tr>
<th>Diameter fibre [µm]</th>
<th>Power [W]</th>
<th>Welding velocity [mm/s]</th>
<th>Energy density $[10^4 \text{ W/m}^2]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>200</td>
<td>33</td>
<td>20.1</td>
</tr>
<tr>
<td>300</td>
<td>275</td>
<td>33</td>
<td>6.9</td>
</tr>
<tr>
<td>600</td>
<td>600</td>
<td>33</td>
<td>3.8</td>
</tr>
<tr>
<td>600</td>
<td>300</td>
<td>7</td>
<td>1.9</td>
</tr>
</tbody>
</table>

The influence of the physical copper limits on the run-on and run-off of the seam were shown in figures 112 and 113. These show that it was possible to have the weld extended to the full length of the seam. The run-on showed no defect, because of the physical copper limit. The weld pool was quenched by the copper limit and no contraction of the seam due to the surface tension could take place.

For the run-off it was hoped to achieve the same phenomena but again it was surprising. For the pulsed mode laser beam experiments comparable results were achieved, the weld pool was not contracted and showed a flat surface on the facet of the strips. In the measurement with white light interferometry it was shown that the decrease in thickness was 90-100 µm.

The surprising element is related to the assumption that the seam was made with keyhole mode welding. The thickness of the workpieces was 0.4 mm, it is therefore interesting to consider how the keyhole could be filled up with material, as it is expected to leave a clear defect as in figure 111. The way of keyhole closure can be described with hydro static pressures [36]. This force pushes the liquid material downwards. A second force is the surface tension, for a closed (i.e. blind) keyhole the surface tension is decreased if the keyhole closes as the surface area is decreased. Besides these two pressures a third force could have influence on the refill of the keyhole, this is the fluid flow momentum in the weld pool. The fluid flow during keyhole welding observed by Matsunawa [37] gives an indication of how this can occur (figure 220).

![Figure 220: Observation with high speed camera of CW laser beam keyhole and weld pool with a beam diameter of 700 µm [37].](image)

In general the keyhole closure does not give a lack of material in the length direction of the seam when welding with a copper limit but it does give a lack of
material in the thickness of the seam at the run-off. This makes the method unsuitable for low defect strip welding, the lack of material is best explained by the fluid flow during welding, as discussed with shadow welding. The exact behaviour at the run-off may be studied better with a high speed video camera.

The influence of the run-on and run-off tabs on the quality of the seam showed an important improvement. Results are shown in figures 114 to 120. In the seam at the work pieces it is shown that no defect is present at the run-on and run-off. The material flow over the workpieces and the run-on and run-off tabs appear to be continuous. With the use of a run-on and run-off tab a sort of continuous seam is created and defects at the start and stop will fall outside of the final workpieces, geometrical irregularities that appeared at these location were not of interest.

For the experiments done with Ultrafort more reproducible results were achieved with ground edges. The creation of a hole at the location of the crossing between the workpieces and the tabs is expected to be dependant on the degree of contact between the workpieces and the tabs. The creation of a hole in the seam could be explained with the fluid flow around the keyhole (figure 20), this flow is discontinuous if a gap is present between the workpieces and the tabs; i.e. the closer the tabs are to the workpieces the better the results.

Between Ultrafort and Durimphy or Phytime a difference in flow behaviour was observed. Durimphy and Phytime were more susceptible to the creation of holes at the crossing of the workpieces and the tabs then Ultrafort. The difference could be described with the fluid behaviour within the weld pool, a higher viscosity or a lower surface tension could decrease the susceptibility of the formation of holes in the seam. The influence of the different facet shapes for Phytime on the quality for the run-on and run-off would be interesting for further testing.

The differences between the focus spot sizes on the surface quality are shown in figures 127 to 132. In general the seam geometry improved with a wider focus spot, the sizes of the ripples decreased and with a focus spot of 450 µm no spatter was present on the workpieces.

The smoothness of the seam was surprisingly different for the different focus spot sizes. On the top side flow lines were present with the 112.5 µm diameter focus spot. The differences between the geometry of the weld pool are difficult to explain from only the layout of the seam. Different factors could have a clear influence on these phenomena, a smaller keyhole will need higher pressures due to the surface tension (see equation 8). To keep the keyhole opened higher vapour pressures will be needed. The keyhole shows a dynamic behaviour [37] and it would be possible that the keyhole even collapses during welding, causing an irregular looking weld pool. A second factor that had an influence on the surface quality is the lower heat input in combination with a higher energy density at the seam. The dissipation of heat can happen at a higher rate causing higher cooling rates which could result in less time for the surface tension to flatten the surface. The cause of the so called flow lines and the oscillations in the weld pool could be related to the energy density of the laser beam. The beam pressure is higher with higher energy densities (see equation 14) this can cause higher fluid flow velocities and an unstable flow pattern.
The geometry of the seam was an important factor in comparing the different welding arrangements, as the surface quality is important for the application in the transmission push-belt. The geometry for sample D110 (see figure 119 and 120) is dominated by the misalignment of the workpieces, although the seam did show a smooth surface with no sharp irregularities. What the influence of the misalignment is on the final geometry of a ring in a transmission push-belt is not clear, this is due to the unknown influence on the rolling process. This process rolls the rings to half of their thickness. It would be interesting for further research to investigate the maximum allowed misalignment.

The sample R24 was welded with the multiple ring welding arrangement (see figures 122 to 125). This proved to be no extra challenge. The results were similar to the sample D110. The crossing between the different workpieces did not appear to be critical. Not much attention has yet been paid to the influence of different geometries of the facet to the final geometry of the crossings. Within this specific area several details for the tolerances of the process can be revealed. The multiple ring welding arrangement was welded in conduction mode, no keyhole was present as no plasma was observed above the seam.

The arrangement of multiple ring welding was performed with the laser beam in a 15° leading position. The influence of this was that the focus spot was not circular but more elliptical. A computer simulation could be performed to indicate the influence of the different focus spot shape on the fluid flow in the weld pool; however, this is beyond the scope of the present work.

With Phytime it was difficult to create full penetration welds and to have no holes in the seam as a result of excessive power. This is shown in figure 126, the surprising parameters are the parameters for sample D110. The difficulties with obtaining full penetration are expected to be caused by the formation of an oxide layer on the surface of the material, when this layer has a higher melting temperature than Phytime. Phytime will melt but the surface can still be solid. To obtain full penetration, without instable fluid flow behaviour creating holes, it seems to be desired to weld with lower velocities as with sample R24. To verify the elements that could form oxides the Ellingham diagram was examined, see figure 221. From this diagram, titanium and aluminium are likely in Durimphy to form an oxidation product, but in Phytime the most likely product formed is FeO. Molybdenum is not shown in this diagram.
Figure 221: The Ellingham diagram shows the formation of oxide products for the different metals, as a function of oxygen and temperature.

In a different study AES measurements were performed on maraging steel powders. One of these was a Ti-free maraging steel, the top-layer had a composition of Fe and O [13]. From the XPS measurements done in that study, it is shown that at a depth of 1500 nm a high oxygen concentration of 30% was found. The other oxygen product that was present on the top surface was SiO$_2$, the average content of Si was 0.03 wt% in the maraging powder used; in Phytite this is in the range of 0 - 0.1%.

With Phytite it is expected that a layer of FeO (melting temperature of 1565 °C [46]), Cr$_2$O$_3$ (melting temperature of 2265°C) and SiO$_2$ (melting temperature of 1710°C [45]) are formed. The melting temperatures of these oxides are higher then the melting point of the maraging steel (1430 -1450 °C). This would support the assumption that an oxide layer causes the more difficult welding behaviour of Phytite.

The shielding gas used was argon with a purity of 99.996%, this had an oxygen content of <10 ppm [47]. If an argon gas is used with a purity of 99.999% and an oxygen content of <5 ppm [48], the amount of corrosion products is likely to be
lowered. The presence of an oxide layer on the topside was also observed with a
CCD camera see figure 222.

![Image of Phytime weld pool during welding with the HL3006D top view, the irregular shaped oxide product is floating on the weld pool.]

Continuous laser beam welding showed possibilities for low defect strip welding. With some arrangements difficulties were faced with fluid flow during welding. The only two arrangements in which this has been successfully prevented are welding with run-on and run-off tabs and multiple ring welding.

4.2. Electron beam welding

From the few experiments done with electron beam welding no new phenomena were observed. The experiments were only done with Ultrafort and the material showed by visual inspection only geometrical defects (see figures 134 and 135). When the weld pool reached a free surface at the side, the end contracted (see figure 136), this is a lower surface energy configuration due to the lower amount of surface area from the weld pool. The wide weld pool showed a material distribution that had a lack of material in the middle (figure 137), this lack of material is difficult to explain as no location was present where an increase of the amount of material was present. It is unknown whether the rolling process could equalize the material distribution. The inhomogeneous distribution after welding could be turned into a homogeneous distribution after rolling.

As no parameters were provided about the focus spot it was not possible to calculate values for the power density or beam pressure. For further experiments electron beam welding could show similar results to laser beam welding, while the energy intensity is typically in the same order as the laser beam. The main difference will be the beam pressure within conduction mode welding. During keyhole welding the vapour pressure and the recoil pressure will dominate. A difference between laser beam welding and electron beam welding will be the amount of reflected energy. For laser beam welding this is significantly different when welding in keyhole
or conduction mode, whereas for electron beam welding this difference is expected to be negligible. For electron beam welding the reflected energy is caused by the radiated energy due to the slowing down of the electrons impacting on the surface (with higher energy also X-ray formation takes place).

For electron beam welding it is expected that the arrangement of welding with a run-on and run-off tab and with multiple ring welding could give positive results similar to continuous laser beam welding. These were not further tested since electron beam welding did not prove to have more advantages over laser beam welding. The disadvantages for electron beam welding versus laser beam welding are the use of the vacuum, the ability to use an electron beam source only on one workstation where a fibre coupled laser beam could work on multiple stations and the possible extra X-ray protection needed during welding.

4.3. Plasma arc welding

The feasibility of the multiple ring welding was proven with the plasma arc welding process, no contraction of the seam appeared and the seam was smooth at the crossings with the different workpieces. This gives opportunities for the possibility to weld a series of rings and weld in a continuous way. The material used was Phytime, this material showed with laser beam welding the most difficulties, which were caused by the oxide layer.

More oxidation products were present on the top of the seam compared with the laser beam welded samples (see figures 138 and 139). The shielding gas used was argon with a purity of 99.996%, when this is substituted with higher purity argon shielding gas (lower oxygen content) improvement may be expected. The low welding velocity would have influence on the time available for the formation of oxides.

It was not possible to compare the process based on heat input with laser beam welding as the voltage drop over the arc was not reported. The surface quality is not as high as the process used presently at VDT (see figures 14 and 142). The parameters of the process were significantly different. Due to the available test setup it was not possible to weld with the same velocity. The comparison for the experiments and the production process at VDT show the potential for improvement of the seam quality.

No focus was put on the influence of the facet of the workpieces, the workpieces were cut and did not have a post-treatment to obtain a smooth facet. The workpieces need to be welded with a facet which is desired for the production of the transmission push-belt.

With optimization of the parameters it can be expected that the surface geometry can be improved, for example by improving the alignment of the workpieces, reducing oxidation products using different welding velocities and/or different shielding gasses, and improving facet dimensions by using facets with a better internal contact. In general plasma welding could be used for the arrangement of welding multiple rings. The process is also expected to be suitable for the
arrangement of welding with a run-on and run-off tab. With this arrangement only small changes are made, no extra challenges are expected because the plasma arc is not expected to be influenced in a detrimental way, as less irregularities are present with this arrangement. A challenge for both arrangements will be the separation of the workpieces from the tabs or the other workpieces, as this should happen without damaging the facets of the workpieces.

4.4. Upset welding

Upset welding proved to be possible with Ultrafort. It is a way to weld rings for a transmission push-belt without defects in the seam and without consumables. The experiments were performed by Strecker and Bihler, from Strecker no parameters were available and from Bihler the parameters were given in section 2.3.

The experiments from Strecker showed more deformation than the experiments done by Bihler. The size of the upset was depending on the distance the electrodes moved towards each other and controlled by the upset force and heat input. The aim for the creation of an upset is to ensure the removal of the defects, like oxides and impurities out of the seam.

For the experiments made by Bihler the heat input profile shows preheating. This was probably done to create a flatter interface by melting the top surface. The direct effect of this preheating could not be compared with other experiments. More differences between the two sets of experiments appeared in the metallurgical analysis, and will be discussed in section 4.2.

A clear disadvantage of upset welding is the need for removal of the flash. This will need further research for the best way of removal, different processes could be possible such as grinding, milling, removal with a chisel, and as a secondary process tumbling, polishing or brushing [49].

4.5. Flash welding

The flash welding experiments were made by Ideal, and were performed with Ultrafort. The geometrical results were similar to the upset welding experiments; they showed that flash welding is a feasible arrangement for ring welding.

Some notes can be made about flash welding, the process uses a preheating process and presses the material when the intersection is still in a fluid phase and this is different to the preheating that was done with the upset welding experiments performed by Bihler where the material was in principle unmelted when applying the upset force. This difference however was not visible in the microstructure. As the parameters were not provided it is difficult to estimate if any melt was present at the onset of the upset force.

A second note is the larger width of the deformed zone that took place on the upside of the flash welded sample (see figure 185), this is likely to be caused by the shape or the placement of the electrode. If the electrodes are placed further away from each other, deformation is allowed over a wider region, it should be possible to reduce this effect to the same level as the underside.
In general the exact influences of the different parameters during flash welding were not tested, but the shape of the flash is expected to have the same dimension as with upset welding. The flash needs to be removed from all sides of the workpieces, the same methods will be available as with upset welding.

4.6. "Mash resistance welding"

For "mash resistance welding" the experiments were done by Bihler. Phytime material was used in this arrangement. Characteristic for the seam was a sharp height defect; the joint created in overlap was not totally deformed to a flat surface. The extra force that was applied reduced the height of the defect up to a level of ~40 μm (see table 17). This defect is different from the misalignment defects shown in the fusion welding arrangements and the latter could be reduced significantly after rolling as the defect is more continuous.

In different publications about mash seam welding the height defect was less then achieved in these experiments (2% increase in thickness versus 10% in the experiments performed by Bihler) [50, 51]. This indicates a greater potential for this process. It must be noted however that these published data were not performed with maraging steel and the materials had lower yield strengths.

A second effect is the presence of burrs in the seam that is a disadvantage of mash resistance welding in comparison to fusion welding. These burrs were present due to the grinding process used for cutting the workpieces. The burrs were also deformed into the seam (see figure 152).

A third effect is the presence of a bulge on the side of the seam (see figure 151). This bulge is formed due to deformation on the side of the workpieces. The material experienced no force that limited the strips to deform in direction of the width of the workpieces the strips showed at this location deformation in the width direction of the workpieces, the material showed no plain strain compression.

Fourthly pores are present in the seam, at the locations where the material shows no signs of melting (see figure 215). These were not eliminated during the welding process. Cracking is easily initiated on these pores. The absence of melting does not necessarily mean the material is not bonded at this location. This could be further investigated with electron microscopy, which was not interesting due to the unsatisfying geometry of the seam.

The exact parameters were not provided by Bihler, this makes it difficult to analyse and compare the arrangement. The welding time should be low, and should be in the order of the upset welding experiments as a comparable way of heating was used. If a higher deformation force is tested a different shape of electrode would be necessary to prevent major deformation on the surface of the workpieces outside the seam.

Due to the height defect and the pores that were observed during welding, it cannot be expected that this process could fully fulfil the desired criteria.
4.7. Materials

The different welding processes were tested with three kinds of maraging steels; Ultrafort, Durimphy and Phytime. The different materials showed different responses as reported in section 3.7.

4.7.1. Ultrafort

Ultrafort was used in different welding processes; laser beam welding, electron beam welding, upset welding and flash welding. In this section the hardening behaviour as a result of the different processes is discussed, as well as the resulting microstructure.

The material is a maraging steel containing chromium instead of cobalt and has a lower nickel content than the other two materials. The final strength will be obtained after precipitation hardening. The influence of the welding process on the local strength of the material will be important as the rings will be rolled after welding, a non uniform strength will cause a non uniform deformation behaviour causing geometrical irregularities after rolling.

The hardness was chosen to indicate the local strength of the material, this can provide a value for the resistance against deformation. Ultrafort showed no significant hardening behaviour as a result of the welding process (see figures 158, 164, 171, 180, 183, and 187). This was surprising as differences in hardness are expected to be related to three factors in the microstructure that were changed with the different welding processes tested. Firstly this is precipitation hardening during welding, including Ni$_3$Mo and Ni$_3$Ti. It could be that the time for diffusion during welding is insufficient for these elements to precipitate in the matrix of the Ultrafort material. The diffusion coefficients are not known of the different elements in the Ultrafort matrix, therefore it is not possible to explain in detail the different hardening behaviour in Ultrafort than in Durimphy and Phytime. Secondly and thirdly are the different grain sizes and dislocation densities. None of these factors showed an influence or a direct correlation with the hardness, for this matrix these factors were apparently not significant.

Most surprising are the experiments for upset welding, the differences in microstructure, as shown in figures 173 and 181, have no influence on the hardness. Although it can be expected that in the heavily deformed structure (figure 179), smaller grains and more dislocations are present than in the non-deformed structure shown in figure 173. Based on the uniform hardness distribution Ultrafort would be an excellent choice for the transmission push-belt. The rolling process would show a uniform deformation due to the uniform strength of the material, no annealing before rolling would be needed. But properties such as the content of TiN particles and the strength after annealing make Ultrafort unsuitable for the push-belt.

The differences between the samples that were upset welded are explained by the heat input into the material. The sample welded by Strecker (figure 173) showed a non-deformed structure, this could be due to two reasons, firstly the material was hot during welding and no cold deformed zone was created. The
second reason could be that recrystallization could have taken place as a post-heat treatment.

The main microstructural constituent of Ultrafort is martensite, this is supported by observations with the different etching reagents. Especially Marble’s reagent shows the presence of the martensitic structure. In samples etched with this reagent only little detail in the grain structure was left due to the uniform attack of martensite.

Dilatometer measurements of Ultrafort show the phase transformation temperatures by a difference in elongation (see figure 223). The austenite start temperature is approximately 640°C, the austenite finish temperature around 740°C and the martensite start temperature is 116°C. A temperature increase was observed for the martensite transformation indicating the exothermic nature of this transformation. The precipitation formation is not as clearly observed in this measurement as was shown in the literature [52]. This is consistent with the observations after welding where no hardening was observed.

At the austenite finish temperature the total martensite content is transformed to austenite. This supports the idea that during annealing at 880°C the total material will be transformed to austenite.

Figure 223: Dilatometry measurement of Ultrafort with a heating rate of 0.97 °C/s, this reveals the martensite start temperature at 116°C and the $A_s \approx 640°C$ and $A_f \approx 740°C$. 

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The microstructure for the different welding processes differed a little. Some differences in morphologies were found near the weld pool. The sizes and extents of these morphologies are dependent on the time and temperature history of the different locations around the fusion zone. The different morphologies showed no significantly different mechanical deformation behaviour as discussed above, but the causes of the different morphologies would be interesting for further research. The time and temperature history can cause different morphologies due to phase transformation to austenite and back to martensite, diffusion of elements and mechanical deformation.

During welding the temperature distribution differs over the seam. The different temperature histories could cause different morphologies in the material. In table 20 the peak temperatures are shown at which transformations in the material are expected.

<table>
<thead>
<tr>
<th>Peak temperature</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 20 °C-500 °C</td>
<td>- No changes in the morphology are expected</td>
</tr>
<tr>
<td>- 500 °C-630°C</td>
<td>- Diffusion of elements forming precipitates</td>
</tr>
<tr>
<td>- 640 °C-740°C</td>
<td>- Structure is partially transformed to austenite and then back to martensite.</td>
</tr>
<tr>
<td>- 740 °C-1430°C</td>
<td>- Structure transformed to austenite and back to martensite, any precipitates present are soluted in the matrix.</td>
</tr>
<tr>
<td>- 1430 °C-1450 °C and higher</td>
<td>- Structure is fully molten, solidified into austenite and finally transformed to martensite.</td>
</tr>
</tbody>
</table>

The diffusion of certain elements is used during aging for the hardening of the material. The diffusion is driven by obtaining the thermodynamically more favourable phases with lower free energies. This is possible when the temperature is in a region where the elements have enough thermal energy to overcome local energy boundaries for diffusion. This will take place at a temperature of about 425°C and is initiated on the grain boundaries (grain boundary diffusion). Elements will also move inside the grains if the temperature is high enough (bulk diffusion). The energetically more favourable phases are expected to be in the martensite phase only, as in this temperature region precipitation hardening will take place. In the austenite a uniform element distribution is expected [8].

The deformation during upset welding and flash welding showed a dark etched zone in the middle of the seam (see figures 181 and 186). This is a deformed structure caused by the pressure applied during welding. This morphology did not show extra hardening, since both the base metal and dark etched zone consist of martensite this can be explained. The minor differences that would result from precipitation or strain are negligible compared to the hardness of the martensite. The base material contains a lath type of martensite that already contains a dense
dislocation structure [6]. The extra dislocations formed due to the deformation may not be a significant increase on top of the amount present in the base metal.

More about the formation of the different morphologies can be learned if a temperature profile is measured during welding for the different welding processes. In combination a study of heat treated samples and local element analyses can give a good overview of the processes behind the formation of the different morphologies.

Ultrafast is not interesting for the application of the transmission push-belt and was only used because of the rounded facet shape. Therefore further investigations concerning the creation of the different morphologies lie outside the scope of this thesis.

4.7.2. Durimphy

The maraging steel that is presently used for the production of the transmission push-belt is Durimphy. From the three materials used in this survey, Durimphy resembles most the different maraging steels reported in the general literature from a chemical composition point of view. Only laser beam welding experiments were done with Durimphy in this study with a continuous wave laser and with shadow welding. As Durimphy is used with plasma arc welding in the production of the push-belts at present, it is included for comparison with the laser welded samples.

There is an interest in using high speed and low heat input welding processes as this effect could minimize hardening of the weld as can be expected from figure 9. This would have advantages for the production of the transmission push-belt since the annealing step after welding would become unnecessary. The formation of aging products within short times was not studied intensively in the literature but an initial hardening process was suggested which forms clusters of hard particles [9].

Durimphy is a martensitic alloy, with a low carbon content. It was delivered in the soft annealed condition, the thermal expansion characteristics are shown in figure 224 [53], these show a dip in the heating curve at about 500°C which is suggested to be the start of the precipitation of Ni₃Mo and Ni₃Ti [54]. If the curve shows a stabilized expansion coefficient the precipitation finish temperature is assumed to be reached. The austenite start and finish temperatures are dependent on the heating rate [52].
The structure that would be expected with fusion welding during one welding cycle is a molten structure in the fusion zone, next to the fusion zone a fully recrystallized zone with possibly some grain growth, the third zone is a partly recrystallized zone, fourthly a hardened zone and lastly a zone where no hardening occurred.

Laser welding was performed with copper limits on the run-on and run-off. These limits appeared to be melted and copper was present in the weld pool. This is unacceptable as the copper is expected to form softer zones. If the copper is melted the copper would become a consumable, which is not acceptable.

The influence of the copper on the solidification was also shown in the longitudinal cross section in figure 192 where some epitaxial grain growth was present near the edge. The copper has a high temperature transfer coefficient, which increases the cooling rate and the crystal growth is oriented in a different direction than in the middle of the seam (see the transverse cross section in figure 191). The austenite grains after solidification are transformed to martensite. The orientation of the austenite grain growth would not influence the properties of the weld significantly.

When etched with Fry's reagent, a fusion zone, a recrystallized zone, a zone visually similar to the base metal, a dark etched zone and the base metal were observed.

The plasma welded samples were etched with Nital. This showed a dark etched zone before annealing and no dark etched zone after annealing. The annealing clearly reduces the presence of the precipitation particles, which are dissolved in the face centered cubic matrix. The reduction of the presence of the precipitates was confirmed by the hardness experiments. For the three executed welding arrangements the hardening was equalized after annealing.

The relatively low amount of hardening that took place with the plasma welding was surprising. This cannot easily be explained; a symmetric profile was expected with an amount of hardening at least as much as was found during laser beam welding because the welding velocity is lower and thus the time for precipitation is higher. The reason could be that due to the long time between welding and measuring the precipitates were partly dissolved again.
A second surprise for the plasma welding was the effect of the nital after annealing, it etches the prior austenite grains only in the weld pool. It seems that the nital reagent etches first the alloy rich areas, this is supported by the attack of the dark-etched zone [10]. In the fusion zone the material solidifies in a columnar way and microsegregation is expected to take place during the dendritic solidification. Therefore alloy rich areas are expected in the fusion zone around the dendrites, the annealing step apparently did not homogenize the total material.

In general the Durimphy material showed good welding properties, the hardness increased during welding in the heat affected zone due to precipitation. The welding velocities tested did not show any parameter area where the increase in hardness was absent. Considering the challenges seen with material flow during shadow welding of Ultrafort, it should not be expected that a suitable welding velocity can be found to prevent the hardening during welding with Durimphy.

4.7.3. Phytime

The material for which the process of ring welding out of thin strip material would be most useful is Phytime. In comparison with Durimphy the major difference in Phytime is that the TiN inclusions are not present. The fatigue failure mode is changed from the TiN inclusions to the surface defects. These defects are most likely introduced by the tumbling process as a large amount of rings are mixed with tumbling stones and water, this is a relative uncontrolled process to deburr the edges of the rings. With strip welding the tumbling can be skipped, which could result in a huge improvement with regard to the life time.

The material was delivered and welded in the cold rolled condition. This can be seen in figure 226, an elongated thin fibre like structure can be seen (on the right, next to the heat affected zone). In the cold rolled structure it was easy to detect the recrystallization. The microstructure of Phytime is a full lath martensite structure, no inclusions were visible with an optical microscope. For Phytime the results resembled the Durimphy material. Plasma arc welding, laser beam welding and mas\n resistance welding were done with Phytime material.

In the Phytime material the grains were largest at the sides of the weld pool and decreased in size towards the dark etched zone (see figure 225). The size of the grains is influenced by the time and temperature which the material experienced. Austenite grain growth seems to have taken place in larger amounts at higher temperatures.
The formation of stable austenite after welding is only expected in the heat affected zone, and only in the zone with a peak temperature under the austenite finish temperature. The depletion (as discussed in section 1.2) of martensite is not expected in the weld pool, this is because the martensite start temperature is 206°C (figure 227) at this temperature the amount of diffusion is small. Austenite formation by diffusion of alloy elements was not observed because the time for massive depletion was not sufficient.

The microstructures of the continuous wave laser beam welding and the plasma arc welding were comparable. The welding velocities were 5 mm/s and 0.8 mm/s, the heat input could not be compared, but with both welding arrangements a partially equiaxed solidification structure was observed.

If Phytme is compared with Durimphy two significant differences are to be noted. First is the influence of the corrosion layer as discussed in the first part of the discussion with continuous laser beam welding. Second is the hardening behaviour during welding see figure 228.
The hardening of the Phytime is significantly more than that of Durimphy. The hardening effect that occurs in the order of seconds should be due to the clustering of alloy components. The formation of precipitates needs no significant incubation time, it can be explained by the nucleation of precipitates (Ni₃Mo) taking place on the dislocations [7]. The difference in the amount of hardening during welding between Durimphy and Phytime could be explained within the synergistic effects between Mo and Co, the Co-content in Phytime is twice the concentration in Durimphy (16 % compared with 8 %). Cobalt reduces the solubility of molybdenum and enhances the precipitation of molybdenum and iron. A second effect could be attributed to a different dislocation density between Durimphy and Phytime, a higher dislocation density (due to the cold rolling structure in Phytime) could increase the amount of nucleation sites.

For the mash resistance welding the sample was etched with nital, a weld nugget was shown in the middle of the seam. The temperature at the location of the weld nugget was above the melting temperature. In the rest of the joint the temperature was below the melting temperature but significant pressure at an elevated temperature was applied, this could have increased the degree of bonding.

The hardness increase for the mash resistance welding was less than with the fusion welding processes. This is expected to be due to the heat input of the process, the welding time is expected to be in the order of 10-50 ms for the heating cycle applied. For the applied current no suggestion could be given but the material is heated locally at the position of the highest electrical resistance where the current flows.

In general Phytime showed fairly good weldability, the passivation layer does influence the welding behaviour of the material and this was noted during laser beam welding. The hardness increase is more significant than with Durimphy but is removed by annealing for 15 minutes at 880°C.
5. Conclusions

In this study the possibilities for welding thin maraging steel were tested, the requirements for the joint were tailored to the demanding application of a transmission push-belt, where especially geometrical and metallurgical defects are of utmost importance. Therefore the focus of the project was on these geometrical and metallurgical defects which occur during welding. A large variety of welding processes were evaluated as well as different ways of utilising these processes. The conclusions of the experiments are summarized in this chapter. These conclusions lead to several recommendations which involve the feasibility of the welding processes and further research that can be done.

Laser beam welding with four different kinds of lasers, electron beam welding, plasma arc welding, resistance upset welding, flash welding and ‘mash resistance’ welding were tested. The tests were executed on three different maraging steels, Ultrafort, Durimphy and Phytome.

The first laser beam welding process is pulsed mode laser beam welding. With this process the possibility was shown to prevent contraction of the seam due to the surface tension. The way to prevent contraction was with a physical copper limit. This was not proven to be a suitable solution because at the run-off of the seam a defect of 60 µm was still present. Further optimization might reduce this defect within acceptable limits. The difference between the run-on and run-off was attributed to the fluid flow during welding. This limits the possibilities for pulsed mode laser beam welding in the context of this study. Other possibilities might be within the use of run-off tabs, but this was not tested as better weld pool dimensions were expected with continuous wave laser beam welding.

The second laser beam welding process was shadow welding. This process is not applicable for low defect strip welding because of the large unstable fluid flow during welding. It did not prove possible to create a joint with a homogeneous metal distribution. There seems to be a relation between the amount of fluid flow and the energy density and/or welding velocity. No solutions are expected for low defect strip welding in combination with shadow welding.

The third laser beam welding process is welding with a line focus optic. It was tested in combination with physical copper limits. No successful results were obtained, the seam contracted in all the fully penetrated experiments. Even though a more thorough optimization is possible for this experiment, it is not expected that this will significantly improve the results since large geometrical defects in the weld pool are present over the full length of the seam.

Finally continuous wave laser beam welding was investigated and this process shows the most potential in achieving the aim of this study. During continuous wave laser beam welding the effects of material flow were also experienced but this was not detrimental for the geometrical criteria when welding with run-on and run-off tabs, or with the multiple ring welding arrangement.

Electron beam welding was only tested bead-on-plate and in a butt weld configuration. Contraction of the seam due to the surface tension was shown here as
well. It can be concluded based on the few experiments that were performed that welding in a butt joint configuration was not proven feasible. It is expected that the same possibilities for electron beam welding and for continuous wave laser beam welding exist. Extra advantages for electron beam welding are not expected and based on cost issues this process is not considered desirable.

Plasma arc welding was tested with the multiple ring welding arrangement. The experiments were done with successful results. Multiple ring welding was shown to be possible. Since this configuration is even more difficult than welding with run-on and run-off tabs it is expected that this arrangement is also feasible for plasma arc welding as well. The challenge in this setup will be the separation of the different workpieces, and necessary post treatment of the separated surfaces.

Upset welding was proven feasible for low defect strip welding, around the seam an upset was present. This upset should be removed with a precise process. The possibilities for the removal should be further investigated. The same conclusions can be drawn for flash butt welding. The extra preheating and melting, characteristic for flash welding is not necessary for welding the strips. Flash welding is thus not preferable for this application.

The so called mash resistance welding did not prove to be successful. The seam showed a considerable number of pores and a thickness increase over the seam was still 10% even after extra deformation. From these characteristics the process is deemed not feasible for low defect strip welding.

Three materials were used; Ultrafort, Durimphy and Phytime. Ultrafort is a cobalt free maraging steel which showed good weldability. It was used because of its availability with the required rounded facet. The material showed no hardening during welding, in contrast to the hardening behaviour of Durimphy of Phytime. The viscosity of the molten metal during welding appeared to be higher which influences the geometry of the fusion zone. Therefore Ultrafort is not an ideal material as it does not show comparable properties to the materials used for the transmission push-belt.

Durimphy showed a good weldability. The material was fully martensitic, there was no transformation of martensite to austenite observed in the heat affected zone. The hardening during welding was significant but could be reduced to the level of the base metal after annealing. No specific metallurgical challenges were faced during welding.

Phytime showed a fairly good weldability. It is a fully martensitic material and welded in the cold rolled structure. The material showed significantly more precipitation hardening during welding than Durimphy. Again this could be solved during annealing. An extra challenge of welding Phytime in comparison with Durimphy was achieving full penetration with high laser beam welding velocities. This problem is caused by the oxidation layer on the material on the underside of the weld pool. A solution was found using lower welding velocities.

A summary of the different experiments is shown in tables 21 and 22. These show a subjective indication based on the results presented in this report for the potential of the different processes. For the technical feasibility in table 21 the scores
are: 1= insufficient, 2= moderate, 3= good. For the technical feasibility of the different welding arrangements all the scores should be moderate or good.

Four criteria are considered. The geometry of the run-on and run-off regions have the same demands but the results were different for the different welding arrangements and therefore described separately. With the surface geometry the surface quality of the seam is considered in the middle of the seam. The metallurgical quality represents the amount and degree of challenges faced with the welding of the material. These criteria result in a technical feasibility of the different welding arrangements.
Table 21: Overview of the different welding arrangements tested, and the technical feasibility of these experimental arrangements (1= insufficient, 2= moderate, 3= good).

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Butt weld</th>
<th>Physical copper limits</th>
<th>Shadow welding with LBW</th>
<th>Physical copper limits</th>
<th>Pulsed mode LBW</th>
<th>Line focus with LBW</th>
<th>Continuous wave LBW</th>
<th>Electron beam welding</th>
<th>Plasma arc welding</th>
<th>But weld with external pressure</th>
<th>Upset welding</th>
<th>Flash welding</th>
<th>&quot;Mash resistance welding&quot;</th>
<th>Heat joint configuration with extra deformation force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry of the run-on region</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>N/A</td>
<td>N/A</td>
<td>1</td>
</tr>
<tr>
<td>Geometry of the run-off region</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>N/A</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>N/A</td>
<td>N/A</td>
<td>1</td>
</tr>
<tr>
<td>Surface geometry</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Metallurgical quality</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Technical feasibility</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>
In table 22 the technical feasible of the different welding arrangements are subjectively considered with respect to different characteristics (criteria) of the welding arrangement. The scores for the different criteria mean: 1= poor, 2= moderate and 3 = good. To the different criteria a subjective weight factor is added to value the criteria with regard to their importance (1= low= negative for the welding arrangement, 2= moderate and 3=high=positive for the welding arrangement). In the total score the weight is multiplied by the score of the different criteria and accumulated. The scores show that the welding arrangements are competitive to each other. No major differences were observed.

Table 22: Overview of the technical feasible processes with a subjective score for different characteristics

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Run-on and run-off tabs</th>
<th>Continuous seam LFW</th>
<th>Multiple ring welding</th>
<th>Plasma arc welding</th>
<th>Upset welding with external pressure</th>
<th>Butt weld with external pressure</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirements fixing process (alignment of workpieces)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Requirements pretreatment</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Mechanical post-treatment</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Requirements post heat treatment</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Corrosion prevention during welding</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Processing speed</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Automate process</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Knowledge of the process within VDT</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total score</td>
<td>36</td>
<td>36</td>
<td>39</td>
<td>39</td>
<td>39</td>
<td>39</td>
<td>39</td>
</tr>
</tbody>
</table>
6. Recommendations

In this study five welding arrangements are proven to be technically feasible for welding thin strip with the desired low amount of defects for the application of the transmission push-belt (see tables 21 and 22). These different welding arrangements have in total about the same score. From these five welding arrangements no arrangement is clearly favourable.

For the fusion welding processes (including plasma arc welding and laser beam welding) the welding arrangement welding with maraging run-on and run-off tabs was possible. The next challenge will be to remove these tabs in an appropriate manner. The facet of the ring should not be damaged during removal and mechanically post-treated to remove any burrs or irregularities left.

This challenge will be even larger with the removal of the different workpieces after multiple ring welding, any material loss will result in damage to the workpieces since the workpieces are in direct contact with each other. The feasibility of this welding arrangement will be dependant on finding an appropriate post-treatment for separating the different workpieces and shaping the facet.

For the resistance welding (upset and flash welding) the challenges are left in the removal of the deformed material that was pushed out of the seam. This deformed material has an irregular form and will need to be removed on the four sides of the workpieces. The surface roughness (Ra) of the topside and underside that will need to be obtained in the final product will need to be in the order of 0.1 – 1.0 μm. The influence of the rolling process on the surface roughness will need to be investigated for the exact requirements for the mechanical post-treatment.

If appropriate post-treatments are found, the welds should be tested on ultimate tensile strength and fatigue. These properties could not be tested in this study as crack initiation would take place on geometrical surface defects and thus no legitimate values would be obtained.

It is advisable to perform further testing with Durimph or Phytime. Ultrafort did not show directly comparable results to the other two materials in terms of weld behaviour and metallurgy.

Based on cost analysis a choice might push this project in a further direction. Since the laser did not prove capable to weld the Durimph and Phytime with high welding velocities, laser welding may not be preferable above plasma arc welding, because the capital costs of a laser are about ten times higher. But it must be noted that the laser used for welding, could as well be used for a post-treatment (e.g. laser cutting).
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