A Study on Micro-gripping Technologies

PROEFSCHRIFT

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To my family

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Summary

In a production activity, the assembly process integrates components from their individual states into a joined state. The development trend of product miniaturization requires the assembly process to be extended from the conventional scale to the micro-scale. This dimensional change leads to the prevalence of predominant physical interactions and effects throughout the assembly process, which produce new challenges in assembly and the enabling technologies. Micro-gripping, as an essential process of micro-assembly, has been the topic of ever-increasing academic research efforts in the last decade. New gripping methods, with varying physical principles and force interactions, are investigated in laboratories in an attempt to handle miniaturized objects. However, micro-gripping is developed with a rather different approach in the industrial domain. The common approaches are to miniaturize and re-engineer the known gripping solutions of the conventional handling process, or to re-design the micro-products in order to fit the known gripping solutions. There exists an evident knowledge gap between principle research and industrial application. Therefore, an expansion of the portfolio of the gripping technology is required.

This thesis focuses on the development of the technology for micro-part gripping with respect to two aspects; **(1)** expansion of the portfolio of the micro-gripping technology by laying the basis for comparison and selection of grip principles; and **(2)** research and exploration of specific grip principles that have better flexibility, higher grip force per unit area of contact and better application potential. The key methodology is to research the gripping technology by relating it with the entire micro-assembly process, and to study the interactions between gripping and other sub-processes of a micro-assembly process.

With respect to the first aspect of this research, a framework for micro-gripping technology is proposed and defined, which structures the understanding of diverse gripping technologies and provides a means to evaluate different gripping methods. The establishment of the framework is achieved in two stages as follows.

In the first stage, an elaborate literature survey with respect to diverse micro-gripping methods is performed. Grip principles and actuation principles are distinguished and defined in this research, which enables all diverse gripping concepts to be categorized by their physical principles. In total, eleven principles are distinguished in this survey. The survey reviews each gripping concept on the principle level, as well as with respect to the general designs aspects, application issues, and different implementation methods.

In the second stage, the framework is defined on the basis of the literature survey and the grip principle development in this research project. The framework covers both principle-related understanding, including force mechanism, and process-related knowledge, including the handling flexibility. The framework is established with a set of criteria, which are finalized from the analysis into the micro-assembly and gripping process, as well as other relevant aspects. A potential application of the framework is then illustrated, combined with a selection method of a grip principle. Five micro-grip principles are presented within this defined framework and include friction gripping, vacuum gripping, electrostatic gripping, capillary gripping and liquid solidification gripping. Within these grip principles, electrostatic gripping and liquid solidification gripping are further researched with experimental and modelling efforts, and the results are presented.

With respect to the second aspect of the research, the liquid solidification grip principle is researched and developed with a view to use in industrial applications. The principle is chosen for its high potential grip force per unit area of contact and good flexibility. This gripping process utilizes the variations of the adhesion forces of the gripping intermediates between solid and liquid phase to perform the gripping and releasing operations. The study is first performed at the grip principle level to determine the most promising concept for further research. In an effort to identify which serves best as a method for variation of adhesion forces, four different physical or chemical processes are investigated. In addition to the use of thermal process, novel process of using magnetic field, electrolysis and UV polymerization are researched. In the end of the analysis, the concept of using water coupled with a thermal process is identified as the most promising solution.

Research steps, including studies of the grip cycle time, the grip force and the gripping process, are carried out in order to develop the liquid solidification gripping to be used in industrial application. Gripper prototypes are developed with specific research goals with respect to this approach: (1) prove the principle and identify application criteria, (2) optimize the process for a short grip cycle, and (3) approach a fully functional gripping system. Each stage includes design, modelling, and experiments.

Experiments are conducted to test the gripper performance and to prove the development. Grip cycle time is evidently improved in comparison to the state of the art research. For a single operation, a grip cycle time of less than 0.5 seconds is achieved in handling low thermally conductive components. For a continuous operation with components that exhibit very high thermal conductivity, the grip cycle time is less than 1.2 seconds. Grip forces are experimentally investigated using a broad range of material parameters. The most influential parameters are the object material, gripping temperature and surface roughness. In general measure, the specific grip forces are approximately 0.5 N/mm^2 for non-metallic parts, and can be larger than 1 N/mm^2 for metallic parts.

Samenvatting

Als onderdeel van een productieactiviteit worden in een assemblageproces afzonderlijke componenten samengevoegd tot een samengesteld geheel. De steeds verdergaande productminiaturisatie dwingt assemblagemethoden te ontwikkelen vanuit conventionele afmetingen naar de microschaal. Deze dimensionele verandering leidt tot een verschuiving in belangrijkheid van fysieke interacties en effecten tijdens het assemblageproces, resulterend in nieuwe uitdagingen voor de te gebruiken assemblagemethoden en technieken. Microgrijpen, als essentieel onderdeel van microassemblage, is in de laatste tien jaar onderwerp geweest van toenemend wetenschappelijk onderzoek. Nieuwe grijpmethoden, met variërende fysische principes en krachteninteracties, worden onderzocht om geminiaturiseerde componenten te kunnen hanteren. In de industrie wordt echter een andere aanpak gehanteerd voor de ontwikkeling van microgrijpoplossingen. De meest voorkomende aanpak is ofwel het miniaturiseren van bestaande grijpoplossingen, of het herontwerpen van de microproducten om ze geschikt te maken voor bestaande grijpoplossingen. Er is een duidelijke kloof in kennis tussen principeonderzoek en industriële toepassing. Om deze reden is een uitbreiding van de portfolio van grijptechnologieën vereist.

Dit proefschrift richt zich op de ontwikkeling van grijptechnologie voor microcomponenten met betrekking tot twee aspecten: **(1)** uitbreiding van de portfolio van microgrijptechnieken door het leggen van een basis voor vergelijking en selectie van grijpprincipes; en **(2)** onderzoek en exploratie van specifieke grijpprincipes met verhoogde flexibiliteit, hogere grijpkracht per oppervlakte-eenheid en betere toepasbaarheid. De hoofdaanpak is het onderzoeken van de grijptechnologie in relatie tot het microassemblageproces als geheel, en het bestuderen van de interacties tussen het grijpen en andere subprocessen van het microassemblageproces.

Met betrekking tot het eerste aspect van dit onderzoek is een raamwerk voor microgrijptechnologie gedefinieerd, dat de kennis van diverse grijptechnologieën structureert en een hulpmiddel verschaft voor het evalueren van verschillende grijpmethoden. Dit raamwerk is tot stand gekomen in twee stadia zoals als volgt omschreven.

In het eerste stadium is een uitgebreide literatuurstudie uitgevoerd met betrekking tot diverse microgrijpmethoden. Grijpprincipes en actuatieprincipes zijn onderscheiden en gedefinieerd, waardoor alle verschillende grijpconcepten kunnen worden gecategoriseerd naar hun fysische principes. In totaal zijn elf principes onderscheiden in dit onderzoek. Het onderzoek beschouwt elk grijpconcept op principeniveau, en ook met

betrekking tot algemene ontwerpaspecten, toepasbaarheid en verschillende uitvoeringsvormen.

In het tweede stadium is het raamwerk gedefinieerd op basis van het literatuuronderzoek en de ontwikkeling van het grijpprincipe in dit onderzoeksproject. Het raamwerk bevat zowel principegerelateerde kennis, inclusief krachtenmechanisme, als procesgerelateerde kennis, inclusief hanteerflexibiliteit. Het raamwerk is voorzien van criteria ontleend aan de analyse van het microassemblage- en grijpproces, evenals andere relevante aspecten. Een potentiële toepassing van het raamwerk is vervolgens getoond, gecombineerd met de selectie van een grijpprincipe. Vijf grijpprincipes zijn gepresenteerd binnen dit gedefinieerde raamwerk: grijpen op basis van wrijving, vacuümgrijpen, elektrostatisch grijpen, grijpen op basis van oppervlaktespanning en grijpen met behulp van bevriezing van vloeistof. Van deze grijpprincipes zijn elektrostatisch grijpen en grijpen met behulp van bevriezing verder onderzocht door middel van experimentele en modelleerwerkzaamheden, en de resultaten zijn gepresenteerd.

Met betrekking tot het tweede aspect in dit onderzoek is het grijpprincipe met behulp van bevriezing onderzocht en ontwikkeld met als doel het gebruik voor industriële toepassing. Dit principe is gekozen vanwege zijn hoge potentiële grijpkracht per eenheid van contactoppervlak en zijn hoge flexibiliteit. Dit grijpprincipe gebruikt het verschil in adhesiekracht tussen de vaste en vloeibare toestand van het grijpmedium voor het grijpen en loslaten van microcomponenten. Het onderzoek is eerst uitgevoerd op principeniveau om het meest veelbelovende concept voor verder onderzoek te bepalen. In een poging om te bepalen welke methode om de adhesiekrachten te variëren het beste is, zijn vier verschillende fysische of chemische methoden onderzocht. Naast onttrekking van warmte zijn ook het gebruik van magnetische velden, elektrolyse en UV polymerisatie onderzocht. Uiteindelijk is bevriezing van water als meest veelbelovende oplossing geselecteerd.

Onderzoeksstappen, zoals studies van de grijpcyclustijd, de grijpkracht en het grijpproces, zijn uitgevoerd met als doel om grijpen op basis van bevriezing industrieel toepasbaar te maken. Grijper prototypen zijn ontwikkeld met specifieke onderzoeksdoelen met als einddoel: (1) bewijzen van het principe en identificeren van toepassingscriteria, (2) optimaliseren van het proces met betrekking tot een korte grijpcyclustijd, en (3) benaderen van een volledig functioneel grijpsysteem. Elk stadium omvat ontwerp, modellering en experimenten.

Experimenten zijn uitgevoerd voor het testen van de grijpprestatie en om de ontwikkeling aan te tonen. De grijpcyclustijd is duidelijk verbeterd ten opzichte van externe onderzoeksresultaten. In individuele handelingen is een grijpcyclustijd bereikt van minder dan 0.5 seconden voor het hanteren van componenten met een lage warmtegeleiding. In een continu proces voor componenten met hoge warmtegeleiding was de grijpcyclustijd minder dan 1.2 seconden. Grijpkrachten zijn experimenteel onderzocht voor een breed spectrum aan materiaalparameters. De meest invloedrijke parameters zijn het objectmateriaal, de grijptemperatuur en de oppervlakteruwheid. In het algemeen zijn de specifieke grijpkrachten ongeveer 0.5 N/mm^2 voor niet-metalen componenten, en kunnen groter zijn dan 1 N/mm^2 voor metalen componenten.

Contents

Nomenclature

Latin Symbol	Description	Units
a	Seebeck coefficient	V K^{-1}
A	Cross-sectional area perpendicular to force	m^2
B	Magnetic flux density	T
C	Capacitance	F
C	Heat capacity *(C_w, C_p)*	J kg^{-1} k^{-1}
d	Diameter	m
E	Energy	J
E	Young's modulus	Pa
F	Force	N
F_B	Grip force on the basis of Benoulli Effect	N
F_E	Electrostatic force	N
F_L	Laplace force	N
F_s	Surface tension force	N
F_T	Tension force	N
F_{vdw}	Van der Waals force	N
G	Geometric property of the TEC	m
H	Lifshitz-van der Waals constant	eV
h_c	Heat transfer coefficient	W m^{-2} K^{-1}
h_l	Latent heat *(h_{lm} , h_{levp})*	J kg^{-1}
I	Moment of inertia	m^4
I	Current	A
k	Material and temperature dependent interaction constant in van der Waals force	J m^6
k	Thermal conductivity	W m^{-1} K^{-1}
L	Characteristic length of an object or a system in scaling laws	m
m	Mass	kg
N	Number	N. A.
p	Resistivity	Ω m

Latin Symbol	Description	Units
Ph	The phase transition number	N. A.
q	Point charge *(q, q')*	C
q	Heat flux, the heat transfer per unit area.	W m^{-2}
Q_i	The power of heat loss or heat flow by means of conduction, convection or thermal radiation. (i = cb, cond, conv, rad…)	W
r	Radius of the contact area	m
r'	Radius of the air inlet	m
R	Resistance	Ω
Ra	Surface roughness	m
t	Time	s
T	Temperature	K or °C
U	Voltage (electric potential difference)	V
V	Velocity	m s^{-1}
V	Volume	m^3
z	Molecules distance in van der Waals force	m
ΔP	Pressure difference	N m^{-2}

Greek Symbol	Description	Units
γ	Surface tension	N m^{-1}
δ	Separation distance Deflection	m
ε	Emissivity	N. A.
ε_0	Permittivity of the free space	F m^{-1} or C^2 N^{-1} m^{-2}
ε_r	Relative permittivity of a material	N A
ε_{vdw}	Interaction energy between two molecules in van der Waals force	J
θ	Contact angle of liquid to solid	rad
λ	Wave length	m
μ	Friction coefficient	N. A.
μ_0	Permeability of space	T m A^{-1}
ρ	Density	Kg m^{-3}
$\rho_{\perp}$	Principle radius of the meniscus in the vertical plane	m
$\rho_{//}$	Principle radius of the meniscus in the horizontal plane	m
σ	Stefan-Boltzmann constant	W m^{-2} K^{-4}

Abbreviation	
1D (2D, 3D)	One Dimensional (Two Dimensional, Three Dimensional)
DOF	Degree of Freedom
FR4	PCB. Woven glass and epoxy
HPLC	High Performance Liquid Chromatography
IC	Integrated Circuit
ICPF	Ionic Conducting Polymer Film
ITO	Indium-Tin-Oxide
MEMS	Micro-Electro Mechanical System
PCB	Printed Circuit Board
SCARA	Selective Compliant Assembly Robot Arm
SEM	Scanning Electron Microscope
SMA	Shape Memory Alloy
SOI	Silicon-on-Insulator
TEC	Thermoelectric Cooling
VDW	Van der Waals

1 Introduction

This thesis focuses on the technology for micro-part gripping, which is an essential part of the micro-assembly process. This chapter outlines the research background and lays the foundation for the following discussions throughout this thesis. In the first section, a brief introduction is given to indicate the scope of the research topic. Important definitions that are made in this research and used in the context are stated in the second section. The third section addresses the scaling laws that are strongly related to the topic of micro-gripping.

1.1 The scope of micro-assembly and micro-handling

Product miniaturization and function integration have become the trend of diverse manufacturing domains, including electronic industries, mechanical industries, chemical industries and biomedical industries. Miniaturized products require fabrication and assembly technologies to extend from the macro-domain to the micro-domain. New challenges with respect to assembly and the enabling technologies, (*i.e.* feeding, handling, joining technologies) have been revealed in this process. Micro-handling, as an important process of micro-assembly, is the research topic of this thesis.

Micro-assembly and micro-handling operations deal with parts with typical dimensions in the range of sub-millimetres to a few millimetres. The part features are typically in the micrometre range. The typical post- joining accuracy in part relations is in the range of 0.1 to 10.0 micrometres. It is worthwhile to notice that, in the micro-domain, the dimensions of a micro-part, micro-part feature and assembly accuracy can be in the same magnitude. As a reference, the typical size of conventional products fit into a box with measurements of 200 mm by 200 mm by 200 mm, with feature sizes in the millimetres to centimetres range. Assembly accuracy can be as small as 10 micrometres. The scales of the macro- and micro- part are illustrated in Figure 1-1.

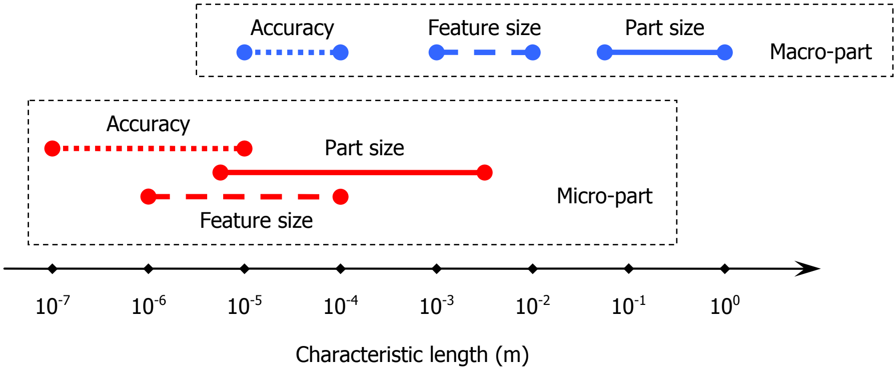


Figure 1-1 Scales of macro- and micro- parts

The manufacturing of micro-sized products stresses the dependency upon the assembly process; it becomes more important, difficult and costly. Due to the multiple functions of the miniaturized products and diverse material being used in a single device, the assembly of the device is more difficult and expensive than fabricating the components. Micro-electronic assembly and printed circuit board assembly benefit from the standardization of geometry of components. Miniaturized electronical components can still be handled with a 2D pickup and place system. However, the more mechanically oriented products often consist of parts with complicated shapes, which commonly require assembly with 3D configuration. Due to space limitation for processing devices and different physical principles that dominate the micro-world, conventional assembly methods often approach their limitation. These difficulties are more obviously seen in the handling process. Extensive research has already been devoted to the development of micro-gripping technology and micro-grippers. Several grip principles are the topic of study, both principles that exist in the macro-domain, and new principles specific to the micro-domain, (*e.g.* electrostatic gripping or adhesive gripping), [Tichem03].

Having stated the above, two aspects require further study and development. Firstly, the understanding of the different grip principles is rather individualistic. Systematic knowledge of the process windows of all these principles is lacking. Secondly, although most of the grip principles have been principally proved, the gap between laboratory testing and industrial application is large and requires further study and development. On the industrial shop floor, micro-handling, even the entire micro-assembly process, often proceeds manually. The time constraint related to the development of a new assembly system for a single product is one of the main reasons behind this. However, it also indicates that micro-assembly systems and the technology being used lack flexibility.

The problem analysis and project definition is stated in detail in Chapter 3.

1.2 Definitions

Micro-handling and micro-gripping are defined and distinguished as follows. "**Micro**" refers to typical dimensions in the range of sub-millimetres to a few millimetres, while "**handling**" refers to operations that aim at changing the position or orientation of a part. It causes motion of a part in at least one Degree of Freedom (DOF). Thus, handling is an operation related to motion.

Gripping is defined as the establishing, maintaining and ending of a kinematic relationship between the part to be gripped and the gripping device. Force interaction is involved in this process to establish, maintain and end the kinematic relation against other forces imposed. This force is defined as the **grip force**. In case the grip force presents as a distributed load applied onto the surface of an object, the **specific grip force** can be defined as the load distribution per unit area. The gripping should ensure no unexpected movement between part and gripper during other operations. A gripping device, (*i.e.* a gripper), may only have the function of maintaining a part, rather than also causing motion in space.

A particular gripping method can be recognized and differentiated from others by examining what force fields are applied during the operation, and the manner in which the force fields are implemented. Accordingly, grip principles and actuation principles can be distinguished and defined. **Grip principle** is defined as the physical principle that causes the force effect necessary to get and maintain the part in a position relative to the gripping device. **Actuation principle** is the principle by which the grip principle is implemented. For some of the grip principles, a variety of actuation principles can be devised. As an example, a gripper which grips a part on the basis of friction between the part and the gripper is usually implemented on the basis of a pair of fingers. This gripping action can be implemented, for instance, by utilization of a mechanism with stiff fingers with (elastic) hinges, or on the basis of deformable piezo-material fingers [Tichem03]. Thus, grip principles and actuation principles are the determinants of the applicability of gripping devices.

1.3 Scaling laws

The force interaction between objects in the micro-domain is quite different from that in the macro-domain. The dominating forces in the macro-domain start to become negligible in the micro-world and vice versa. The reason for this is that the volume related forces, (*e.g.* weight and inertia) decrease faster than the surface related forces, (*e.g.* Van der Waals force, electrostatic force). The change of the relative importance of forces influences the behaviour of micro-systems and the assembly methods of these systems, phenomena that are unfamiliar to the macro-domain appear. These are all described by scaling laws. Surface related forces often disturb the handling process, which can be witnessed in both the pick and release stages of handling. A part may jump to a handling tool before the operation is executed because the electrostatic interaction between the handling tool and the part is prevailing over the gravity. It can be difficult to separate the part from the handling tool at the release stage due to surface tension, which is also surface dependent. Special attention is paid to the elimination of negative influences in the handling operations. However, strategies that positively use these surface related forces in handling micro-parts are also seen in the research field. Diverse handling methods that utilize the surface related forces have been demonstrated.

Descriptions of scaling laws with a broad scope can been found in literature. The following sections are dedicated to summarizing the scaling laws that are relevant to part gripping and objects interactions.

1.3.1 Basic physical parameters

"*L*" is defined as a single dimensional scalar for the length of an object or a system. Hence, the surface scales with the second power of *L*; and the volume scales the third power of *L*. It is assumed that the same factor is applied to all dimensions. The geometrical dependency is described as "proportional to *L* or to the second power of *L* or to the third power of *L*", written as "$\propto L$, $\propto L^2$ or $\propto L^3$".

In the following discussion, Continuum mechanics is still applied. It is assumed that the physical properties of the micro-system are not changed at the molecular level. Accordingly, density, viscosity, thermal conductivity, electrical conductivity, Young's modulus, *etc.* are not scaled with the scaling of geometry.

Mass is proportional to volume and therefore, proportional to the third power of *L*, while inertia is also proportional to the third power of *L*.

1.3.2 Surface tension

Surface tension can be observed in a liquid bridge between two objects. Surface tension becomes relatively large in comparison with other forces during the miniaturization. It is supposed that a concave meniscus is formed between two solid objects, a handling tool and a component, as shown in Figure 1-2.

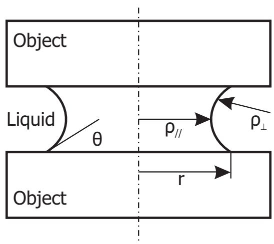


Figure 1-2 Sketch of liquid in contact with objects

The surface tension is the sum of the so-called tension force, F_T, and Laplace force, F_L. The tension force is produced by the intermolecular bonding of the liquid to the solid interface [Lambert05]. It can be described as:

$$F_T = 2\pi r\gamma \sin\theta \Rightarrow F_T \propto L, \tag{1-1}$$

with r as the radius of the contact area, γ as the tension of the surface (Nm^{-1}, water as 72 mNm^{-1}), and θ as the contact angle of liquid to solid.

The Laplace force is caused by the pressure difference of the inside and outside of the meniscus, over the liquid to solid contact area:

$$F_L = \pi r^2 \gamma (\frac{1}{\rho_\perp} - \frac{1}{\rho_{//}}) \Rightarrow F_L \propto L' \tag{1-2}$$

with the $\rho_{//}$ and $\rho_\perp$ as the principle radii of the meniscus in the horizontal plane and the vertical plane, respectively, shown in Figure 1-2.

The overall surface tension equals:

$$F_S = F_T + F_L \Rightarrow F \propto L. \tag{1-3}$$

It is important to note that the surface tension, although named as a surface force, is proportional to the first power of L. The surface tension force to gravity ratio is consequently very promising for handling applications in the downscaled assembly process.

1.3.3 Van der Waals force

Van der Waals (VDW) force is named after the Dutch physicist and chemist Johannes Diderik Van der Waals, who first recognized the force. The force refers to a set of intermolecular forces that arise from the attraction of dipoles. The set of intermolecular forces include London forces (which arise from shifts in electron cloud distribution), Keesom forces (which arise from fixed or angle-averaged dipoles) and Debye forces (which arise from free or rotation dipoles).

The interaction energy ε_{vdw} between two molecules across a distance z can be written with a material and temperature dependent interaction constant k:

$$\varepsilon_{vdw} = -\frac{k}{z^6}. \tag{1-4}$$

It can be seen that the interaction energy is decreasing by the sixth power of the distance increasing. The VDW force dominates at the level of molecular length scale and acts as the bonding force of atoms or molecules. Apart from the molecular length scale, the force can normally be neglected in comparison with gravity or other forces.

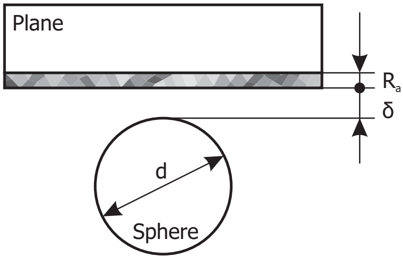


Figure 1-3 Sphere-plane model, with surface roughness

The VDW force between two macro-objects can be estimated by the Lifshitz model, which is a macroscopic approach. This means that a large quantity of atoms or molecules is involved, but the geometrical dimensions can still be in the sub-millimetre scale. From a commonly referenced model, shown in Figure 1-3, the VDW force between a sphere and a plane is described with [Bowling88]:

$$F_{vdw} = \frac{Hd}{16\pi\delta^2}, \tag{1-5}$$

with H as the Lifshitz - Van der Waals constant, d as the diameter of the sphere, and δ as the separation distance between the sphere and the plane.

The magnitude of the VDW force is influenced by surface roughness (Ra), [Arai96], [Zhou00]; the equation can be modified as:

$$F_{vdwr} = (\frac{\delta}{\delta + R_a/2})^2 F_{vdw}. \tag{1-6}$$

From the preceding equations, the VDW force between a spherical object and a plane surface is proportional to the diameter of the sphere, consequently scales with L. However, the influences of surface roughness and separation distance are more significant. Considering these parameters, the VDW force reduces at the second power, proportional to the increase of surface roughness or separation distance. Consequently, the force plays a role only in the micro-domain. It should be noted that in the actual condition, the VDW force rarely individually presents. The surface tension force caused by the natural humidity, and electrostatic force due to potential differences, always accompany it. The coexistence of these adhesion forces occur frequently in micro-domain.

1.3.4 Electrostatic force

Electrostatic force F_E is defined as the electrical force of repulsion or attraction induced by an electric field, with the field strength E. According to Coulomb's Law, the electrostatic force F_E between two point charges q and q', at a distance δ, can be described as:

$$F_E = \frac{1}{4\pi\varepsilon_0\varepsilon_r}\frac{qq'}{\delta^2}, \tag{1-7}$$

with the ε_0 as the permittivity of the vacuum ($\varepsilon_0 \approx 8.854\times10^{-12}$ F/m), ε_r as the relative permittivity of a material (also called dielectric constant), which is usually given relative to that of the vacuum ($\varepsilon_r = 1$ in vacuum condition).

Electrostatic forces acting between parallel plates can be described as:

$$F_E = \frac{1}{2}\frac{\varepsilon_0\varepsilon_r A U^2}{\delta^2} \propto L^2, \tag{1-8}$$

with U as the applied voltage between the plates, A as the surface area perpendicular to the vector F_E and δ as the separation distance between the two plates.

From the equation above, the electrostatic force is proportional to the surface area of the object. Meanwhile, it is inversely proportional to the second power of the separation distance. When the force is used as the driving principle or grip principle in micro-handling, the separation distance is usually minimized. The advantage of the scaling factor is that it can be understood that F_E is proportional to the second power of L.

Due to the nature of the electrostatic charge, the force appears frequently as a disturbing force in micro-handling. This phenomenon is illustrated in Figure 1-4.

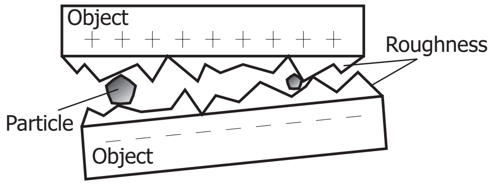


Figure 1-4 Electrostatic interaction between objects

The electrostatic charge can arise from charge transfer or charge generation. Charge accumulation in a natural condition is a component of the general adhesion force, which often disturbs a micro-operation, for which special measures are needed. When two objects with different electrical potential come into contact, the dielectric layers or nonconductive particles between the objects will create a gap, typically in the order of a few tens to a hundred nanometres range.

1.3.5 Magnetic force

A magnetic field can be generated by a permanent magnet or an electromagnet. In physics, a magnetic field is that part of the electromagnetic field that exerts a force on a moving charge. The magnetic force between two closely attracting surfaces can be calculated by:

$$F_M = \frac{AB}{2\mu_0}, \tag{1-9}$$

with A as the area of facing surface, B as the magnetic flux density between them, and μ_0 as the permeability of space (unit: TmA^{-1}). It appears from this function that the magnetic force is proportional to the second power of L. However, when the scaling of the magnetic flux density is considered, according to [Trimmer89], the force is proportional to the third or fourth power of L.

1.3.6 Pressure difference

Forces that arise by pressure difference are obviously proportional to the second power of L.

1.3.7 Friction

The classical friction model is known as Coulomb friction (named after Charles-Augustin de Coulomb). The force is proportional to both the normal force of the contact surface, and the coefficient of friction. This force is exerted in the direction opposite the object's motion, thus it is an opposing force. Considering a macro-scale object lying on a horizontal plane, the normal force is the gravity of the object. Hence, the maximum friction force in the contact is proportional to the mass, and thus, the third power of L. For a micro-scaled object in the same situation, the surface related forces, as above mentioned must be considered in this model. Therefore, the normal force becomes the sum of the gravity and the overall adhesion force. The friction force in the micro-domain is proportional to the second power of the L, because of the dominance of adhesion.

When an object is gripped on its vertical surfaces, the same analysis above applies. For a macro-scaled object, the maximum friction force is proportional to the grip force applied to the grip surface. In the case of lifting a part, the friction force is at least equal to the gravity of the part. For a micro-scaled object in handling, the maximum friction force becomes proportional to the sum of the grip force and the overall adhesion force. In many situations, the overall adhesion force is so great that it causes enough friction force to overcome the gravity of a small object. This explains why a small particle can stick on a vertical surface without falling off.

1.3.8 Heat transfer

Heat transfer is energy in transit due to a temperature difference. The process refers to three modes, defined as conduction, convection and thermal radiation, [Incropera96]. In the micro-assembly field, heat transfer is an important aspect. It is often used as driving principle or sensing method. The heat transfer rate determines the response speed of thermal sensors, or the operation frequency of a thermal actuator. Although the heat transfer occurs mainly at a contact surface, the heat flow is not simply proportional to the area.

The heat conduction rate through a surface can be described by Fourier's law. The heat flux q, which is the rate of heat transfer per unit area, may be expressed as:

$$q = k\frac{dT}{dL}\cdot \tag{1-10}$$

The heat flow or heat loss through a surface is:

$$Q_{cond} = qA = kA\frac{dT}{dL} \propto L\Delta T, \tag{1-11}$$

with k as the thermal conductivity, a material dependent constant, T the temperature. From this equation, it is concluded that within a limited range of temperature change (as the k remains constant); the conductive heat flow is proportional to L.

There are two types of convection, free convection and forced convection. In micro-systems, free convection is of more concern. Q_{conv} can be expressed as:

$$Q_{conv} = h_C A\Delta T, \tag{1-12}$$

with h_c as the heat transfer coefficient for convection, a geometrically and dimensionally dependent parameter. For macro-scaled systems, the convection coefficient can be regarded as a constant, whereas in micro-scaled system, it is nearly inversely proportional to the characteristic length. As a result, the convection heat flow in micro-systems is proportional to L, [Peirs98].

In principle, thermal radiation is electromagnetic radiation emitted from the surface of an object, which is due to the object's temperature. The heat flow can be described as:

$$Q_{rad} = \varepsilon A\sigma T^4 \propto L^2T^4, \tag{1-13}$$

with ε as the emissivity, σ is the Stefan-Boltzmann constant. From the formula, it is clear that the radiation power is proportional to the second power of L. It should also be noted that for normal micro-systems or micro-operations, heat transfer by means of radiation is very limited compared to heat conduction. Therefore, it is generally negligible in the thermal analysis of micro-systems.

As discussed above, the thermal behaviour of micro-systems is generally proportional to the characteristic length (*L*) of the system. More detailed discussions about the scaling effects of heat transfer and its application in micro-gripping can be found in Chapter 7 and Chapter 8.

1.3.9 Further important issues linked to scaling

In addition to the scaling laws discussed above, further issues related to scaling influence the production methods of micro-products. They affect the processes of micro-assembly and micro-handling, which are often the motivations for the development of new handling tools. The most critical issues are the operational space and operational force.

With products minimizing in size, more components are being squeezed into smaller spaces, and the components' density becomes higher. Consequently, the space remaining for tools to access decreases significantly and some of the conventional assembly methods are challenged. With the size of the components minimizing, the total area and the numbers of accessible surfaces on the component open to the access of handling tools are limited. Conventional gripping methods are often incapable of setting up sufficient and stable gripping contacts.

The operation forces involved in an assembly process are not always downscaled proportionally to the downscaling of part dimensions. A small component may receive a relatively high operation force in an assembly process, (*e.g.* pressing or welding). This force can easily break an inappropriate gripping contact or damage the component. It is therefore crucial to develop handling methods that are better suited to the characteristics of the micro-assembly process. At the very least, a gripping tool developed for micro-assembly must guarantee adequate contact stiffness in a restricted space.

1.3.10 Summary of scaling laws

The above discussed scaling laws are summarized in Table 1-1.

	Gravity	**Surface tension**	**VDW force**	**Electro-static force**	**Magnetic force**	**Pressure difference**	**Friction**	**Heat transfer**
Scales with	L^3	L	L	L^2	$L^3 \sim L^4$	L^2	L^2	L

Table 1-1 Summary of scaling laws

2 State of the art research on micro-assembly and industrial approach

As explained in Chapter 1, the focus of this research is with respect to micro-systems assembly and micro-gripping in particular. The main goal of this chapter is to discuss the micro-gripping process within the larger context of the assembly and manufacturing of micro-products.

The survey in this chapter is the basis for the problem statement in Chapter 3.

2.1 Micro-systems and the challenges of micro-system assembly

Micro-system is a popular term referred to in research nowadays. However, a clear definition of this term is difficult to find. To this end, it can be explained from different aspects.

Micro-system development has two essential aspects, “miniaturization” and “functions integration”. The first aspect refers to a dimensional change of a functional system. A micro-system is usually composed of sub-millimetre sized parts, and is often equipped with dedicated features of a few micrometres in size. For example, a micro-loud speaker for a small hearing aid is approximately 15 cubic millimetres, while a micro-motor has a diameter of less than 5 mm and a length of less than 10 mm. A gear system of a micro-motor is shown in Figure 2-1. However, the ability to build a small system is certainly not the ultimate goal of developing a micro-system. The second aspect refers to the creation of multifunctional products, which are the main driving forces behind the miniaturization trend. Smaller systems, which have the same or even more functionality than larger systems, allow the same job to be accomplished with less energy and less material. Therefore, there can be more functionality in a single product without adding mass, size or cost. Smaller systems also enable the operation of smaller quantities, for instance, smaller liquid dosing volume, less sample consumption in various tests, the ability to make or sense smaller paces in motion. Micro-systems have higher eigenfrequencies, which make them react quicker and run faster.

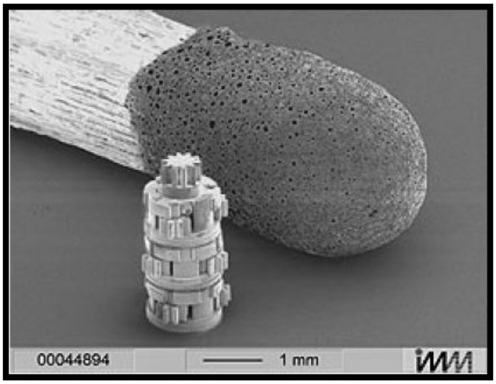


Figure 2-1 Micro-motor gear system (source: Institut für Mikrotechnik Mainz, Germany)

Micro-systems with different appearances and names are widely found in the semiconductor domain, mechatronical domain, and the bio-medical domain. The technology used to create MEMS (Micro-Electro Mechanical System) enables one to make 2.5D to 3D structures, based upon the silicon processing method. Conventional mechanical designs are then transferred to MEMS design. Various sensors and actuators, which are implemented in mechanical structures, are realized on silicon wafers. For instance, pressure sensors and acceleration sensors can now be made by wafer technology. Meanwhile, topics such as Hybrid MEMS, system on chip, chip to chip bonding, and wafer to wafer bonding are increasingly being addressed in academic research. Micro-systems function in various application domains. Micro-sensors built with MEMS technology, such as force sensors and acceleration sensors, are widely used in the car industry. For instance, acceleration sensors are used to trigger airbags. In the biomedical domain, biosensors, implanted micro-pumps or drug-delivery systems are frequently seen. Micro-filters and micro-reactors are becoming widespread throughout the chemical and food industries.

Two aspects contribute to difficulties in the assembly of a micro-scale system. One is the necessity of guaranteeing sufficient accuracy and successful functions integration in the limited space. The other aspect is the requirement of the integration of a broad variety of materials. Again, using the micro-loud speaker as an example, although only a few millimetres in size, the speaker is equipped with an electronic circuit, magnets, a voice coil as the driving unit, and a driving pin and membrane to produce sound. In order to guarantee the functions of the system, the assembly process must guarantee accurate positioning, joining and connections, while also the assembly accuracy in 6 degrees of freedom. Dedicated tools and operation processes are generally required for components manipulation and assembly.

In a micro-system, because of the multi-disciplinary integration, there is more diversity in the material combination and assembly process combination than in conventional systems. Optical lenses may need to be mounted on a silicon wafer, or fluidic interconnects may need to be integrated into a tiny system while preventing leakage.

Different materials must be bonded together with certain strength, [Seigneur06]. All of these issues must be taken into account in organizing an assembly process, and in designing an assembly system. With respect to the handling systems, the process and material compatibilities must also be clearly understood.

2.2 From a conventional to a micro-assembly process

In the macro-domain, the assembly method, referred to as the main structure of an assembly process, can be characterised as the handling of individual parts from a loose state to a connected state, by means of functions (manipulators, *etc.*), which are product external. In the micro-domain, other methods are being explored. An overview on the basis of a literature survey is discussed in [Tichem02], see Figure 2-2.

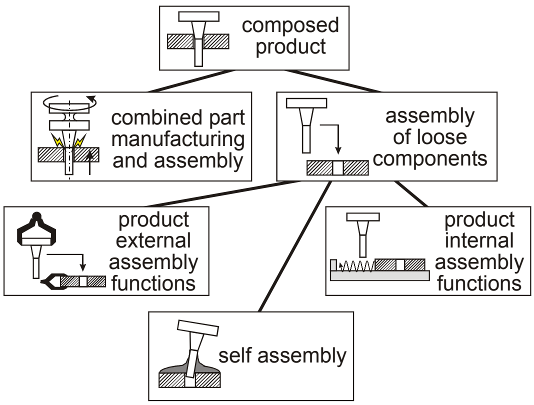


Figure 2-2 Overview of micro-assembly methods [Tichem02]

The overall goal of each method is to create a composed micro-product. A method which is often used in the micro-domain is assembly using "product external assembly functions". At the system level, micro-factory, and module micro-systems are two common solutions. At the technology level, handling technology plays a very important role. This means that manipulators or human operators handle parts and join them together. The innovation in external assembly method is based on the development of techniques for part feeding [Vorstenbosch04], [Turitto06], gripping, micro-robotics [Fatikow96], tele-manipulation [Codourey97] and sensor controlled assembly. However, in addition to this method, other methods are being explored. One option is to create a composed product on the basis of the integration of part manufacturing and assembly operations. For example, in [Langen95], an approach to creating a peg-in-hole combination using EDM and ultrasonic insertion operations is presented. Another option is to assemble products using functionality, which is integrated with the product. This approach is explored in a project focus on optical interconnects, carried out by the Delft University of Technology, [Henneken04], [Henneken08]. Finally, the self-assembly method is based on the fact that in a random process, parts are put together. When their mutual distances decrease, certain force mechanisms start to control the part position and attract them into a final position. Examples have been seen with electrostatic force or surface tension force based self-assembly [Böhringer01], [Lazarou06].

2.3 Micro-factory

The term "micro-factory" was first proposed in the 1990s, by the Mechanical Engineering Laboratory (MEL), Japan. The system combines part fabrication, an internal transfer system and an assembly operation in one small manufacturing station, [Okazaki02]. This research topic has become quite popular. An increasing number of research groups are developing diverse micro-factories and modules, and are trying to transfer the manufacturing concept from laboratory prototype to industrial application.

The motives behind the micro-factory concept are strongly based on economical reasons. Attempts are made to realize a more flexible manufacturing system, while increasing system modularity, whereby a system can be easily reconfigured for new products, or can quickly change the production volume. Efforts to reduce the floor space, energy consumption, and the cost for manufacturing environmental controls, (*e.g.* temperature, clean room) have also been made. Experiments also aim to shorten the logistic chain, and to bring the manufacturing closer to the suppliers or end users.

The micro-factory developed by MEL [Okazaki02] is shown in Figure 2-3. The entire system contains a micro-lathe, a micro-milling machine, a micro-press machine, a micro-transfer arm and a micro-manipulator. All components of the desktop machining micro-factory have been integrated into a single portable box, approximately 625x490x380 mm^3 in size. The system is controlled manually, using two multi-DOF joysticks and a vision aid.

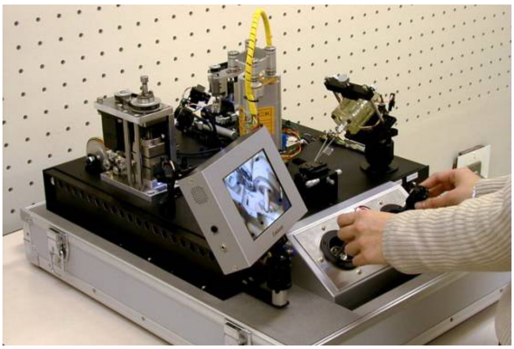


Figure 2-3 Micro-factory, by MEL, Japan

EPFL and CSEM of Switzerland, proposed a micro-factory, which attempts to increase the degree of modularity, [Verettas06]. Several modules can be combined for the assembly of a product. Each module is dedicated to several assembly operations. For reconfiguration of the production line, one or more modules can easily be changed. In Figure 2-4, the possible layout of the micro-factory (left), and a prototype of a single module (right) are shown.

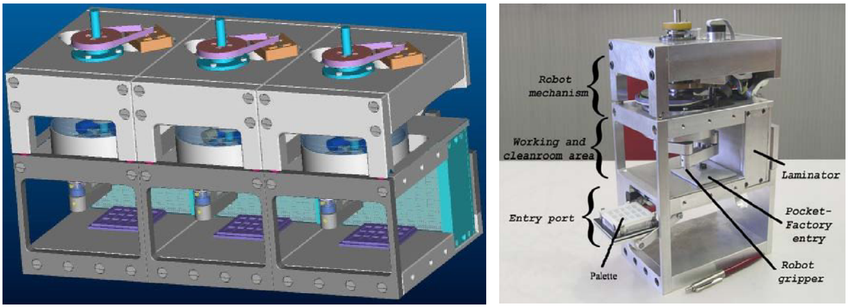


Figure 2-4 Modular based micro-factory (EPFL, CSEM)

Other research institutes are also focussing on micro-factory topics. These include LAB (France) [Descourvières06], TU Delft (the Netherlands) [Langen06], IPA (Germany) [Gaugel03], and MSL (USA).

2.4 Industrial approaches towards micro-assembly

Micro-assembly research is currently in an early stage. It is therefore important to obtain a solid understanding of the complexity of industrial problems.

Investigations have been carried out with various companies, which are active in micro-product development and assembly [Tichem04]. Two companies, for confidentiality reasons, referred to as Company A and B, operate in the market as a system engineer and integrator, and develop and produce production and test systems for a wide variety of industries. Company A produces mainly high volume products, while Company B produces mainly low volume products. A number of their often globally operating customers are manufacturers of micro-products. One company, referred to as Company C, develops and produces opto-electronic components for consumer electronics. The company also engineers its own assembly systems. Another company, referred to as Company D, develops and builds machinery for electronic component assembly. The limited number of companies examined in this thesis does not allow for definitive conclusions, but the issues put forward are used for reference in carrying out this research.

The following issues are discussed in this section:

- The complexity of micro-assembly operations;
- New micro-assembly technologies: need and focus;
- Feasibility of standardization and modularisation; and
- Automation and outsourcing in micro-assembly.

2.4.1 The complexity of micro-assembly operations

In the domain of micro-gripping, substantial attention is paid to the investigation of new principles and their ability to deliver forces for picking up very small parts. However, the analysis of a principle to deliver a certain force is severely limited from an industrial perspective. Several other aspects also play a role, such as cycle time, robustness and flexibility, which are certainly important for industrial application. The exploration, understanding and development of these principles should also be performed from these perspectives. As in some assembly cases, complexities such as handling parts in deep holes, large joining forces, among other aspects, may be considered.

2.4.2 New micro-assembly technologies: need and focus

Due to the specific characteristics of the micro-domain, micro-assembly is said to require completely new methods and techniques. Obviously, the truth of this statement depends heavily upon the characteristic length scale of the parts. Products that fit into the micro-mechanical domain, as considered by Companies A and C, can, despite certain small part dimensions, be assembled manually using techniques that are scaled down on the basis of their macro-domain counterparts. Automation is a subject that is discussed in more detail later in this section.

Industry is inclined to use available techniques because of their proven performance and reliability. In the domain of micro-gripping, Companies A and C indicated that the principles that they mostly used were gripping on the basis of friction (finger-based grippers) and on the basis of vacuum. Companies spend money and effort on re-engineering the product in such a way that it can be assembled on the basis of known and proven technologies, rather than risking problems in production due to immature assembly techniques. However, both companies also indicated that they are approaching the limits of what can be done with existing principles and techniques. New techniques with adequate application knowledge are needed in industrial implementations.

2.4.3 Feasibility of standardization and modularisation

One clearly visible trend in assembly systems is the development of modular assembly system concepts. Modularisation requires standardization on different levels, including the operation and workstation level. It offers potential benefits in terms of rapid re-configuration of assembly systems, rather than re-engineering, and an increased use of proven technologies. In addition, the cost of the system can be distributed over several product variants and generations of products. This reasoning is true for both macro and micro-domain products. Modularisation and standardization have been mentioned as preconditions for keeping assembly in western economies. A critical question should be asked at this juncture: can a relevant portion of the assembly system be standardized? A relevant portion of the assembly system will always remain product-specific (gripping, feeding, fixating, and joining). However, in micro-assembly, an additional problem exists, as operations are often quite specific, and in many cases, the limits of technologies are being approached. Currently, there is insufficient knowledge on micro-assembly processes. Furthermore, the product design is difficult to standardize, and guidelines for product design for micro-assembly are not yet available. Companies A and B both have modular approaches in their assembly solutions. It is interesting to note that the modularity in the assembly platform and machinery level is more feasible than in the process level. Standardized motion, a sensing system and a robot are introduced for specific and dedicated assembly processes on uniform operation platforms.

It is also interesting to note the comparison with electronics assembly. Company D also indicated that in the electronics domain, "odd components" are increasingly picked and placed. The variation in size, shape, and functionality increases. However, until recently, there has been a high level of standardization compared to mechanical assembly.

In conclusion, the feasibility of standardization and modular approaches to assembly systems and processes in the micro-domain needs to be investigated. The industrial state of development in micro-assembly implies that a primary focus on new technology for the small scale is needed.

2.4.4 Automation and outsourcing in micro-assembly

In the macro-domain, flexible automation of the assembly of families of products has not reached industrial penetration as expected. Although several reasons can be cited, cost efficiency is certainly one of the most important, which explains the trend for outsourcing to low-wage countries. It has often been stated that product miniaturization will eventually make manual assembly technically impossible. How do the companies perceive this?

The industrial reality is that even large volumes of highly miniaturized parts, with dimensions in the sub-mm range, are assembled manually or semi-automatically, mainly due to reasons of cost, flexibility and variation. In the case of a manual or semi-automatic process, outsourcing to low-wage countries is still an important mechanism to reduce the labour cost involved.

Figure 2-5 shows an example of a to-be-assembled part, which is handled semi-automatically, despite the very small part dimensions, and the related difficulties in manual assembly. The part shown in the figure is a drive pin for a micro-loud speaker, and is assembled semi-automatically. While looking at it with a camera, the operator picks up the part using tweezers and a wooden toothpick, and positions it in a die. The counterpart is put in a fixture. The tool, on which the die is attached, finishes the assembly operation, which consists of a positioning action of a 90 degree rotation of the die, followed by a joining operation. Company A develops the supporting equipment for this operation, while the assembly work is done in Poland.

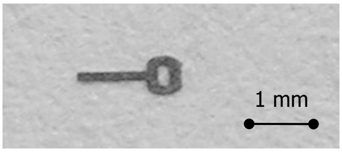


Figure 2-5 Drive pin for a micro-loud speaker, assembled semi-automatically

In conclusion, for the part dimensions shown here, automation is not necessarily the only option. The competition with low-wage manual operation remains an issue. Semi-automation may be an appropriate solution for these products. Again, this implies that increasing the flexibility of an assembly system is a way to maintain the competence of assembly automation. There is a clear need for better developed gripping devices and systems.

3 Problem analysis and project definition

This chapter refines the research problem and outlines the goals of this research project. The structure of the remainder of the thesis is stated at the end of this chapter.

3.1 Problem analysis

In the academic field, there has been extensive research undertaken with respect to different gripping methods. Some of the developments appear promising from the research perspective, but have not yet been used in applications. From the industrial studies, it is evident that industries continue to experiment with existing and known grip principles, even when considerable reengineering efforts are required. What is lacking in this field are, (1) sufficiently developed grip principles that are applicable, and (2) the knowledge of how to implement them.

The main challenge for the present project is identified as the expansion of the portfolio of micro-gripping technology, taking into account the specific characteristics of the micro-parts to be handled, and the micro-assembly operations to be carried out. This includes two main tasks:

- Research on a number of selected grip principles and their applicability in order to gain a systematic understanding and to generate structured knowledge; and
- Investigation of specific gripping technologies and development of micro-grippers on the basis of one or more selected grip principles.

Of particular interest in this project are those principles that are based on the use of changing adhesive forces (*e.g.* contact forces between parts), since (1) they usually need only one surface of contact, and (2) are usually very flexible in terms of the parts that can be gripped (geometry, material type).

The technical goal is to develop technology which allows gripping parts applicable for the micro-domain, and which meet the following requirements:

- Ability to grip parts with small dimensions or small features. The implication of the small size is that the parts are often delicate, and offer very little material to make contact with;
- Ability to grip a wide variety of parts, (*i.e.* the technology needs to be flexible);

- Ability to grip parts with low cycle time. Assembly operations are performed in approximately 1 or 2 seconds cycle time, which means that the time for gripping and releasing the part should be within 1 second; and
- Ability to deliver sufficient force, not only for lifting the part, but in some cases, to withstand forces that occur during joining operations.

The research questions addressed can therefore be formulated as follows:

- What is the applicability of a number of selected principles for gripping micro-parts? What criteria can be used to quantify this applicability? In this investigation, a broad set of micro-grip principles is considered.
- In what way can (a) promising grip principle(s) be used in the design of a prototype micro-gripper, which meets industrial demands in terms of flexibility (parts that can be gripped), grip force, speed (cycle time of gripping and releasing a part), reliability and cost per operation?
- In what way can a developed micro-gripper be optimally used? What are the possibilities and limitations (process windows)? What are the implications for the product and part design?

3.2 Defined goals

It is the aim of this project to deliver the following knowledge and concrete results:

Classification and (semi-)quantitative comparison of a variety of micro-grip principles. Quantification of the process windows of a variety of micro-grip principles for pick-up and release of micro-parts in terms of a set of criteria will be examined. The process window describes, in a quantitative or semi-quantitative way, the possibilities and limitations of a technique.

Development of micro-gripping technology towards industrial application. Gripper prototypes will be designed and realised in an iterative development process. For a more comprehensive understanding, the physics behind the grip principles will be investigated; models of the process will be developed; gripping systems will be tested in laboratory experiments.

3.3 Structure of this thesis

The following discussions are structured in two parts. Part I defines a framework for micro-gripping process window. Part II describes the technology development of liquid solidification gripping methods towards industrial applications. General conclusions are discussed at the end of both parts.

In Chapter 4, a review of the major known gripping methods is undertaken. Different gripping technologies are differentiated and presented on the grip principle level. On the basis of the definitions given in Chapter 1, a total of 11 grip principles are examined in this chapter. The aspects of physical principles, actuation principles, model of grip forces and examples are described under each principle. With the extensive knowledge of the different grip principles, this chapter is the foundation of the framework in Chapter 5.

In Chapter 5, the framework of classifying micro-grip principles is presented. The process windows of grip principles are summarized within the framework. In order to define the criteria for the framework, micro-gripping operations are investigated and analyzed with respect to the general micro-assembly process. The analysis is not limited to the interaction between a gripper and a part, but also covers the analysis of the interaction between gripping and other processes within micro-assembly. A set of criteria is yielded for the framework, which represents gripping contact issues, process and equipment issues, and economical issues. Micro-grip principles are summarized with this framework. In this process, both the information of grip principles gathered from literature survey, and knowledge gained from own research work are used. Electrostatic gripping is specifically studied in the project, while modelling efforts and experimental results are presented in this chapter.

Firstly, from the framework, it can be concluded that the grip force and flexibility are the most important aspects for application. Secondly, a clear gap exists between gripping research and the actual demands of applications. An industrial application gripping system involves more issues than those that have been approached with research efforts. Consequently, the second part of this research work focuses on developing a flexible gripping method for use in industrial application.

Part II begins with Chapter 6. Liquid solidification gripping, which works on the basis of the phase changing of certain intermediate materials, is selected for further development for its relatively high grip force and flexibility. In Chapter 6, this gripping method is investigated on the principle level. Different energy exchange methods that cause the phase changing are theoretically and experimentally investigated. Among electrical-magnetic, opto-chemical, and thermal methods, the latter is selected due to its application advantages. Water is selected as the gripping intermediate.

Three development stages for specific research goals are detailed in Chapter 7. The objectives are (1) to prove the principle and identify application parameters, (2) to optimize the process for short gripping cycle, and (3) to approach a fully functional gripping system. The designs applied to different stages and the development of gripping operation strategies are stated respectively.

Chapter 8 discusses the thermal model used for the prototype design for the final development.

In Chapter 9, the experimental analysis of the gripping process is presented, with the main objective being to evaluate the application criteria of this grip principle. Therefore, the grip cycle time and grip force are emphasized. A large variety of combinations of part materials, surface properties, volume of gripping intermediates, and operation temperatures are analyzed.

Chapter 10 draws general conclusions of the entire research work, and provides some recommendations for future work.

Part I. Framework for classification of micro-grip principles

The discussion in this part is dedicated to the portfolio of the micro-gripping technology, *i.e.* a systematic understanding of different gripping technologies. A framework is developed, which contains and structures the knowledge of micro-gripping from both principle and application aspects.

In Chapter 4, a review of the major known grip principles is given on the basis of literature study. The physical mechanism of each collected grip principle is described, and gripper examples are presented.

In Chapter 5, a set of criteria is defined on the basis of an analysis of the micro-assembly process and related issues. At the conclusion, grip principles are summarized and classified within the framework. The electrostatic grip principle is studied in this research; the modelling and experimental results are stated in this chapter.

4 Review of micro-gripping technologies

In this chapter, a review of different gripping methods is undertaken, subject to the grip principle applied. A total of 11 grip principles is identified in this work. The physical principle, actuation principle, model of grip force and examples are stated for each principle. The information is gathered on the basis of a literature study and research within this project. Compared to what was previously available in the field, the review offers a more complete knowledge assortment of the different grip principles. The knowledge addressed in this chapter will be the foundation of identifying the process window of each grip principle. Other reviews of the micro-gripping technologies from different perspectives can be found in [Lambert05], [Peirs01], and [Grutzeck02].

This chapter begins with an analysis of the gripping process. The steps of a gripping operation and the characteristics of target components are clarified. In Sections 4.2 and 4.3, overviews are given of micro-grip principles and part releasing strategies, respectively. There are 11 basic grip principles in total, and 8 releasing strategies are identified. In Sections 4.4 to 4.14, all grip principles are reviewed individually. Their physical principles, application aspects are described, and examples of gripper designs are categorized with respect to their actuation principles.

4.1 Micro-gripping process

Micro-gripping is one of the essential processes of the entire micro-assembly activity. As stated in Chapter 1, gripping is defined as establishing, maintaining and ending a kinematic relationship between the part to be gripped and the gripping device. The process is illustrated in Figure 4-1. This definition clarifies two aspects of the gripping process. Firstly, gripping is based on the kinematic relationship between the part and the gripping device. Secondly, there are three phases in the gripping process, in which force interactions (grip force) play a role, namely establishing, maintaining and ending the kinematic interaction. The “kinematic interaction” is not restricted to a relation via contact, since both contact and non-contact gripping methods are being used and researched in the micro-domain. The gripping process actually establishes a temporary connection between the gripper and the part via the kinematic relationship. The strength of this kinematic relationship is referred to as “the stiffness of the gripping connection” or “the grip stiffness”. It can be described as the resistance of the gripping connection to deflection or deformation by a force imposed on it.

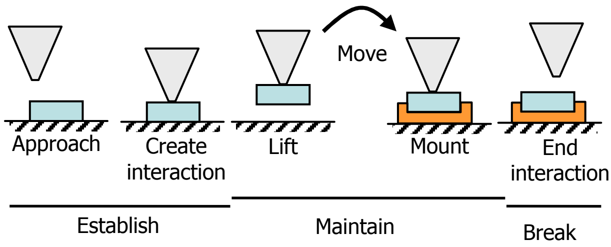


Figure 4-1 Gripping is defined as establishing, maintaining and ending a kinematic relationship between the part and the gripping device

The grip principle, as defined in Chapter 1, is the physical principle that is utilized for the generation of the force between the part to be gripped and the gripping device. Well-known principles include friction, as applied in finger-based grippers, and pressure difference, as applied in vacuum grippers. Grip principles, whose application is limited to the micro-domain, include electrostatic gripping, and surface tension-based gripping, or gripping on the basis of optical pressure.

A common problem in gripping is that many of the solutions are inflexible, and can only handle a limited number of part types. The specific characteristics of parts in the micro-domain necessitate and allow rethinking of the solutions to be used for part gripping. These characteristics include:

- The overall small part dimensions and the corresponding low weight of the parts;
- The sensitivity of parts to adhesion, which is both a problem in handling and an opportunity for applying adhesion force-based gripping methods;
- The small amount of material/surface available for force interaction between part and gripping device (e.g. parts with open structure); and
- The high potential for damaging parts.

4.2 Overview of principles for micro-gripping

As mentioned previously, the grip principle and actuation principle are determinants of the applicability of the gripping device. Each of the principles can only fit into specific application fields. The goal of the research is to improve the understanding of the applicability or to come to a proper selection of grip principles. There are 11 micro-grip principles that can be distinguished, as derived from a literature search. See Figure 4-2. [Tichem03]

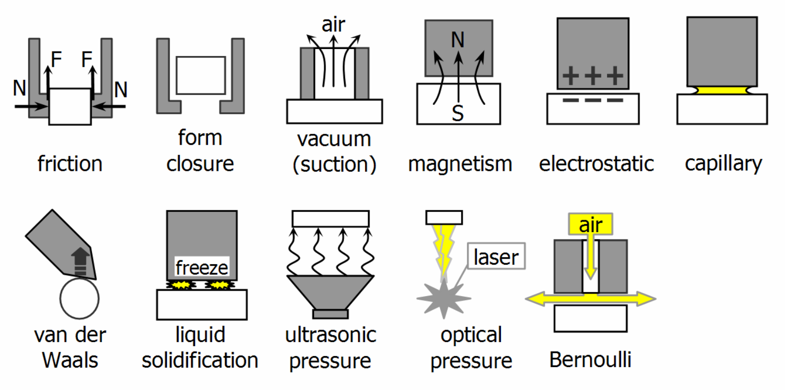


Figure 4-2 Micro-grip principles

Certain grip principles have been thoroughly studied and used in designs, including friction based gripping [Volland02] and vacuum based gripping [Zesch97], [Bos08]. Many examples of these designs can be found in a variety of operational environments. By properly determining the shape, material and size of gripper fingers, they can be fitted for gripping a series of micro-parts. However, this is not easily done for thin, flat and fragile parts (e.g. spacer rings). Force control and cycle time garnered much attention in the research. As an example of this, shape memory alloy (SMA) is used as an actuator for open-close grippers. The disadvantages are that the grip force is difficult to control and the device requires some time for phase transformation, by means of changing temperature, which limits the achievable cycle time.

Vacuum based gripping is a scaled down solution from the macro-domain. In a gripping process, it exhibits high flexibility with a short cycle time. Further research work is required with respect to position control and release strategy.

A liquid solidification gripper, which grips objects by freezing liquid intermediate, is demonstrated in [Patent US 6431622B1]. The approach is rather new for gripping; with respect to this field of research, further study must be applied to the actuation principle, cycle time, release strategy and accuracy. Similar approach by depositing ion in stead of dosing liquid can be found in preparation of microscopic samples, [Mayer07]. This handling method creates a temporary weld between the tool and the target object. The Bernoulli Effect has also demonstrated its ability to lift small parts. Further research is also needed in this area to maximize the effect, and to properly apply it to applications.

Many principles are rarely used industrially due to their inherent limitations. These include Van der Waals force and optical pressure, which are only applicable to very small particles. Likewise the magnetic gripping is rarely used, which only work on magnetizers.

4.3 Overview of releasing strategies

As the indispensable operation of part gripping, part releasing strategies must be considered. It becomes evident from the scaling laws discussed in Chapter 1 that the overall adhesion forces often dominate in micro-handling, and thus part releasing becomes more difficult than gripping. A gripping contact can be ended naturally by the weight of the part or by fixating the part before release. If neither of these situations applies, a releasing strategy must be adopted to finish the gripping process. Figure 4-3 shows a collection of releasing strategies. It should be noted that the application of releasing strategies may correspond to different grip principles.

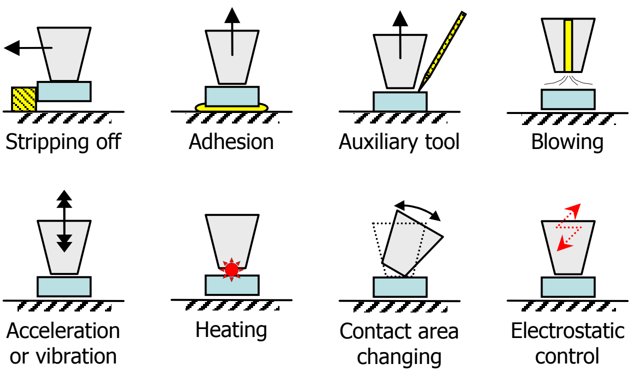


Figure 4-3 Releasing strategies (reproduced from [Arai95], [Porta07])

A brief description of each releasing strategy is given as follows:

- Stripping off: The gripping contact is ended by moving the part against a structure, which causes the breakage of the gripping connection. The structure is normally an edge where the part is positioned to.
- Adhesion: The part can be fixated before moving the gripper away. The fixation can be temporary or permanent; it can be implemented by gluing, clamping, general adhesion, *etc*.
- Auxiliary tool: The part is pushed away from the gripper by an additional tool, *e.g.* a needle.
- Blowing: The part is blown away from the gripper.
- Acceleration or vibration: Using acceleration or vibration introduces a dynamic force to the part. When the acceleration force acting on the part exceeds the adhesion with the gripper, the part is released.
- Heating: Heating the gripping contact will reduce the liquid bridge between the gripper and part. This leads to a reduction of the adhesion force.
- Contact area change: Changing the contact area between the gripper and part will influence the force in proportion to the contact area.

- Electrostatic control: Changing the charging condition of the gripping contact can reduce the electrostatic force between the gripper and part. This can be performed by inversing the charging voltage, or discharging, or grounding.

It should be noted that a grip principle may correspond with more than one releasing strategy. The non-contact grip principles often do not need any releasing methods. The implementation of diverse releasing strategies will be described with respect to different grip principles in the following sections.

4.4 Friction gripping

Friction gripping is well-known in conventional scaled operations. It can be seen as a down-scaled solution from the macro-domain. Normally, a pair of fingers approaches a work piece from two opposite directions and picks it up. In some cases, designs with more fingers are seen.

4.4.1 Grip principle and general design aspects

In a common handling scenario, an object is held on a pair of surfaces on opposite sides by gripper fingers. The maximum grip force, as discussed in Chapter 1, is proportional to the friction coefficient of the surfaces and the sum of the grip force and the overall adhesion force.

Due to the small dimension and low mass of the target part, more critical issues emerge in relation to how to restrict the force instead of how to generate sufficient force, both in gripping and releasing. The aspect to be considered in design is attempting to hold a part firmly in place, without damaging the contact surfaces. In one approach, force controlled gripper designs are demonstrated in [Greitmann96], [Kirchhoff06], [Pérez06]. Part releasing is an important aspect for this grip principle. In order to let the part easily drop off by its own gravity, design and operation strategies are used to reduce the adhesion force by reducing the contact surface [Arai96], humidity, capillary force, electrostatic charges, or by performing the operation in a liquid environment [Hériban06]. In addition to only using the gravity, more releasing strategies can be employed. For instance, the part can be fixed at the release location before opening the gripper, or stripping the part off at a sharp edge, or loosening with an auxiliary tool (*e.g.* a needle), by introducing acceleration or vibration, [Arai95], [Porta07].

4.4.2 Actuation principles

Several principles are used to actuate the gripper fingers. Including electrostatic actuators, shape memory alloys, pneumatic actuators, piezo-actuators, bimorph actuators, among others, can be used for this purpose.

Gripper design with electrostatic actuator: An electrostatic comb drive is a common actuator for this type of gripper. The comb drive generates a linear motion under certain electrical potential. This motion is then transferred to move the gripper fingers towards each other for the gripping operation. The pulling force of a comb drive can be calculated with following equation, which was also mentioned in Chapter 1:

$$F_E = \frac{1}{2}\frac{\varepsilon_0 \varepsilon_r A U^2}{\delta^2} \tag{4-1}$$

with ε_0 as the permittivity of the vacuum ($\varepsilon_0 \approx 8.854 \times 10^{-12}$ F/m), ε_r as the relative permittivity of a material (ε_r = 1 in vacuum condition), A as the surface area perpendicular to the vector F_E, U as the applied voltage between the plates, and δ as the separation distance between the two plates.

Grippers made with different materials are found in literature studies. The advantage of this grip principle is that the grip force can be realized in a large range, and the handling dimension can vary in the range of a few micrometres to a few millimetres, depending on the design.

As stated in [Volland02], a micro-gripper is fabricated from SOI (silicon-on-insulator) wafers, by surface and bulk micromachining fabrication technology. The gripper is shown in Figure 4-4. A deflection of 20 μm, at a driving voltage of 80 V, was achieved.

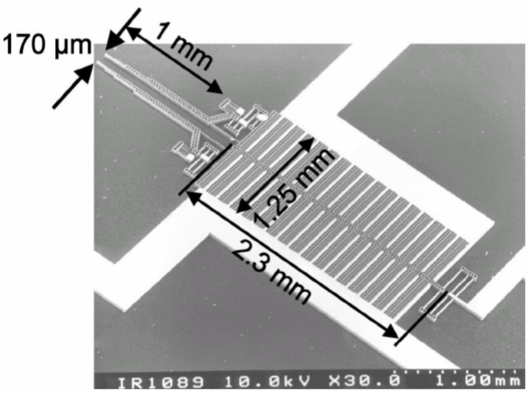


Figure 4-4 Dimensions of the micro-gripper [Volland02]

A Polysilicon electrostatic micro-gripper, as shown in Figure 4-5, is demonstrated in [Kim92], which features a flexible cantilever comb-drive arm, with bidirectional actuation, and an over-range protector. When a 20 V potential was applied, a gripping range of approximately 10 micrometres was achieved.

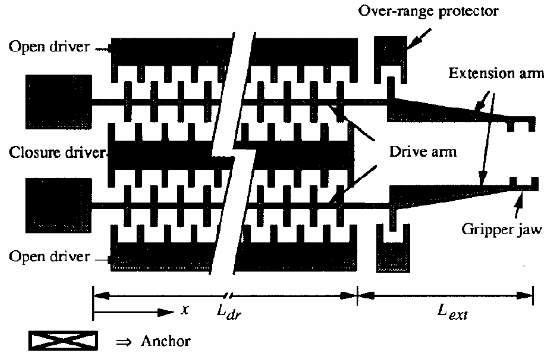


Figure 4-5 Schematic figure of the Polysilicon gripper [Kim92]

Gripper Design with electromagnetic actuator: In addition to the comb drive, a voice-coil is used in micro-scale devices, which is also frequently applied in macro-size electromagnetic actuators. As addressed in [Chang03], a mesoscopic gripper system is realizable, with a size of approximately 1 cm^3 for clean room operations. The operational accuracy of the mechanism is approximately 5 μm. For the mesoscopic scale, a voice-coil actuator is sufficient to provide an actuating force of bilateral direction with a gripping range of up to 2 mm. In the gripping operation, an IC chip with 0.5 gram can be held and transported under open-loop control. The gripper mechanism is shown in Figure 4-6.

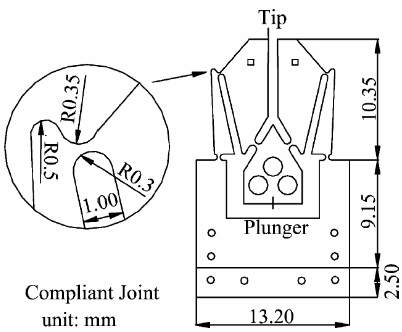


Figure 4-6 A mesoscopic gripper mechanism [Chang03]

Shape memory alloy driven micro-grippers: Shape memory alloy (SMA) was first developed in 1962–1963. Its name refers to the kind of metal that "remembers" its geometry. After the material is deformed from its "remembered" geometry, it can regain this shape by normal heating or simply unloading (pseudo-elasticity or super-elasticity). These properties are due to a temperature-dependent and stress-dependent martensitic phase transformation from a low-symmetry to a highly symmetric crystallographic structure. Although SMA is much weaker than normal construction steel, it can be an interesting material for making micro-scale actuators.

A micro-gripper prototype made from TiNi, measuring 2 mm by 5.8 mm by 0.23 mm, is shown in [Kohl02]. A maximum stroke of 300 μm and a maximum grip force of 35 mN are reported. The positioning accuracy is approximately 2 μm, while the phase transformation time is approximately 140 ms. The schematic structure of the gripper design and a prototype in gripping an optical fibre with a diameter of 140 μm are shown in Figure 4-7.

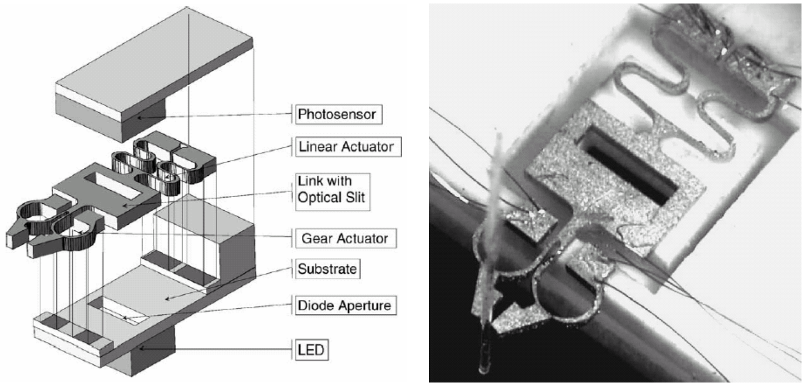


Figure 4-7 The gripper design (left), and gripper in handling fibre (right), [Kohl02]

Micro-gripper with pneumatic actuator: A micro-gripper design is shown in [Bütefisch02]. The gripper is equipped with two pneumatic pistons, one for opening the jaw, and one for closing it. The structure is shown in Figure 4-8. The overall dimensions of the cylinder are approximately 6.6 mm by 5 mm by 1.5 mm. Displacement of up to 600 μm, with a grip force of over 10 mN, is achieved at frequencies of over 150 Hz.

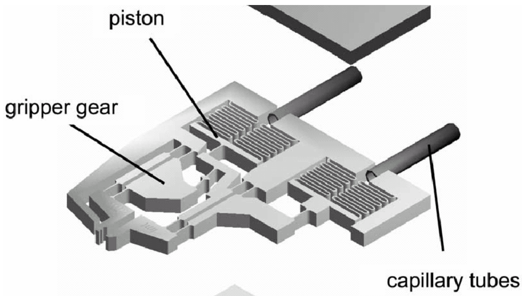


Figure 4-8 Schematic structure of a pneumatic driven micro-gripper [Bütefisch02]

Micro-grippers with piezo-actuators: When subjecting a piezoelectric material to a high voltage, the shape of the material can be changed slightly. Based on this property, the piezo-crystal is used for fine motion and high accuracy positioning actuators. A piezo-actuator has a very high response frequency, typically in the range of Kilohertz to Megahertz. In one application method, this kind of actuator is used directly as gripper fingers for fine pickup and placement operations, *e.g.* [Haddab00], [Agnus03]. In another application method, it is also used to drive certain small mechanisms to perform a gripping operation, *e.g.* [Menciassi02]. In the second means, the motion of the actuator is normally scaled up by the gear ratio of the gripper mechanism, and the gripping operation is performed by gripper jaws/fingers.

A gripper that uses a piezo-actuator to drive flexible hinges for the gripping operation is reported in [Menciassi02]. The design is shown in Figure 4-9. The gripper was produced in a superelastic alloy. With a driving voltage of 150 V, a tip displacement of approximately 395 μm per finger was measured, and a grip force of up to 178 mN was observed.

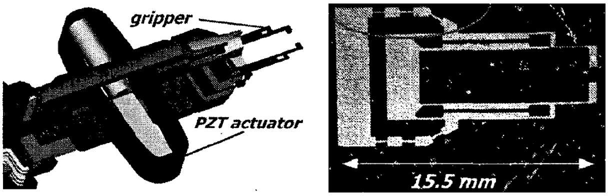


Figure 4-9 Gripper driven by piezo-actuator [Menciassi02]

4.5 Form closure gripping

Form closure gripping is a conventional principle seen in macro-assembly, and is used in a few specific micro-gripping applications.

4.5.1 Grip principle and general design aspects

Two kinds of applicable designs are found in the literature studies, namely, a gripper with an active fingers matrix, and a gripper with a pair of adaptive passive fingers.

The first kind of gripper is found in the handling of biological materials. There are two main critical issues for implementing the gripper. Sufficient space is needed for the gripper to approach the object in order to enclose or hold it, and space is needed for the same purpose when releasing the object. In biological applications, the gripping operation receives sufficient space, particularly because gripping often occurs in a liquid. In the gripping process, it is important to prevent bio-cells from mechanical damage. Form closure gripping in particular enables this to be achieved. In this case, positioning accuracy is of less concern. Two examples of this are outlined below, which are based on the “active fingers matrix” design.

The second kind of gripper is developed as a dedicated tool for handling a particular type of micro-part. Specific features are built into the gripper fingers, which adapts to the inversed features on the target parts. This kind of gripper is not interchangeable for gripping other types of parts, because the form closure is built via the specific features on the gripper and part. The designs are highly dependent upon the particular application.

4.5.2 Actuation principles

Pneumatic driven: A design of a micro-cage is proposed in [Ok99] for application in biological micro-objects. The pneumatic actuation principle was used due to its limited influence on biological cells.

The micro-cage, shown in Figure 4-10, is equipped with 12 fingers each measuring 940 μm long by 80 μm wide. The resulting cage diameter is approximately 900 μm in diameter. In the research a live particle with a diameter of approximately 400 μm was successfully captured.

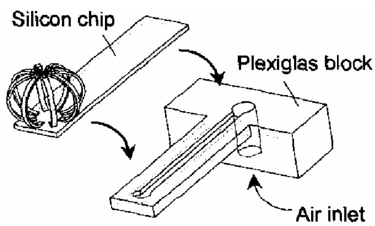


Figure 4-10 Micro-cage for micro-objects [Ok99]

Micro-gripper driven by Ionic Conducting Polymer Film actuator: The Ionic Conducting Polymer Film (ICPF) actuator has the advantage of producing a large deflection with a relatively small input voltage (~5 V). It allows many new applications to be developed, particularly for applications in biology, underwater MEMS, and artificial muscles. In the following example, [Kwok01], a laser micromachining process is introduced to fabricate arrays of ICPF gripping devices, which can potentially be integrated onto a PCB board to develop a micromanipulation system.

Individual multi-finger grippers with dimensions of 200 μm x 200 μm x 3000 μm for each finger, were realized. Fingers were successfully actuated underwater with a 15 V DC voltage. Grippers can be fabricated in a batch. Figure 4-11 shows a batch of ICPF grippers and the performance test. It shows that a closed space is formed by adding a certain voltage to the actuators.

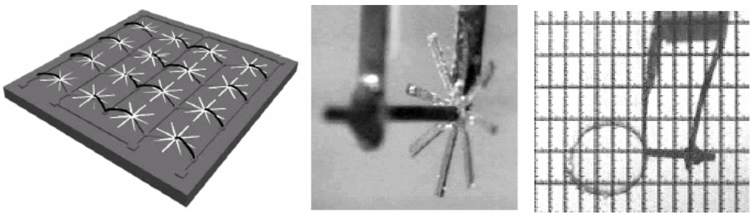


Figure 4-11 ICPF actuated micro-gripper [Kwok01]

Compliant passive micro-gripper: A design of a passive gripper for handling small silicon parts is reported in [Dechev04]. The micro-gripper is able to grasp a micro-part, remove it from the chip, move it by two independent axes and help to join it to another micro-part. The dimensions of the gripper are 380 μm by 410 μm. The gripper is equipped with two compliant gripper fingers and specific geometries at the gripper tips to perform gripping, holding, joining and releasing operations. To grip a part, the gripper tip is pushed against the interface feature on the target part with an insertion force. When the inserting force develops, the gripper fingers are pushed open; meanwhile the part is slid in and engaged with the gripper. The gripping connection is robust enough to hold the part in position and push the part to join with other micro-parts. After the joining process, the part is forced to slide out of the gripper by pulling the gripper away. Figure 4-12 shows the operation method of the gripper on the left, and a micro-gripper with a part in gripped position on the right.

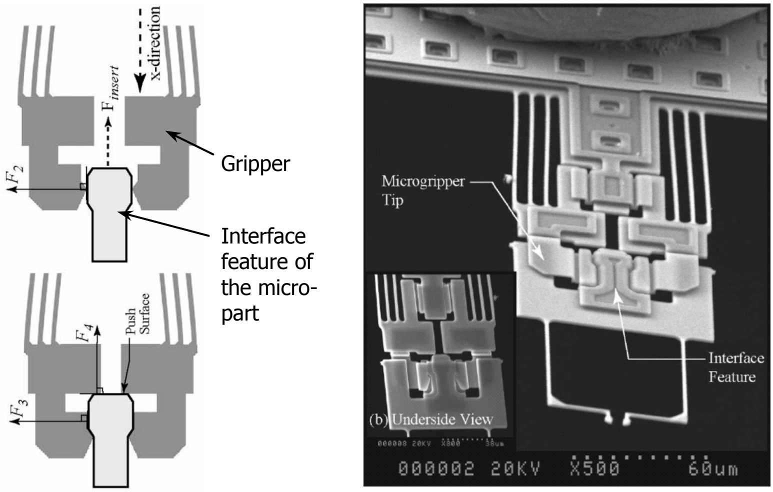


Figure 4-12 Gripper operation (left), Micro-part in gripped position (right) [Dechev04]

4.6 Vacuum gripping

Vacuum gripping is also known as suction-based gripping. This principle is commonly used in conventional pick and place operation of macro- to meso- dimension components. In micro-gripping applications, it is one of most widely used principles, *e.g.* in placing electronic components on printed circuit boards.

4.6.1 Grip principle and general design aspects

Vacuum gripping works on the basis of the pressure difference between that of the grip area and that of the ambience. In a normal working environment, the ambience pressure is approximately 1 bar (unless in an environment with increased pressure), which limits the maximum specific grip force not exceeding this value. However, it does not restrict the application of this principle in diverse industrial fields.

The principle offers good flexibility with respect to gripping and assembly system design and implementation. Air is sucked in via a small opening at the end of a tube which forms the gripping nozzle. The dimension of the gripping nozzle can be made from a diameter of many centimetres or larger to the tens of micrometres range. If necessary, several nozzles can be combined for a single gripping operation, [Ansel02]. Clogging of the gripping nozzle sometimes hinders the gripping operation. The probability of clogging can be reduced by using proper filters and by controlling the operational environment.

The common solution of part releasing is to switch off the air pressure to let the part drop with its own weight or to reverse the air flow to blow the part off. In some situations when very high positioning accuracy is demanded or adhesion force is disruptive, the component is fixed to the releasing position before the gripping ends. In principle, the vacuum grip principle matches other releasing strategies, at least with auxiliary tools or stripping off.

4.6.2 Actuation principles

Driven by vacuum pump: As reported in [Zesch97], in combination with a computer controlled vacuum unit, a glass pipette is able to perform pick and place operations of 50 μm-300 μm sized metallic and non-metallic particles, with a success rate of approximately 75%. To release stuck objects (the other 25%), three release strategies have been proposed. The tool has been integrated into the ETHZ NanoRobot, [Zesch97], which allows building 2D and 3D structures in a reasonable time.

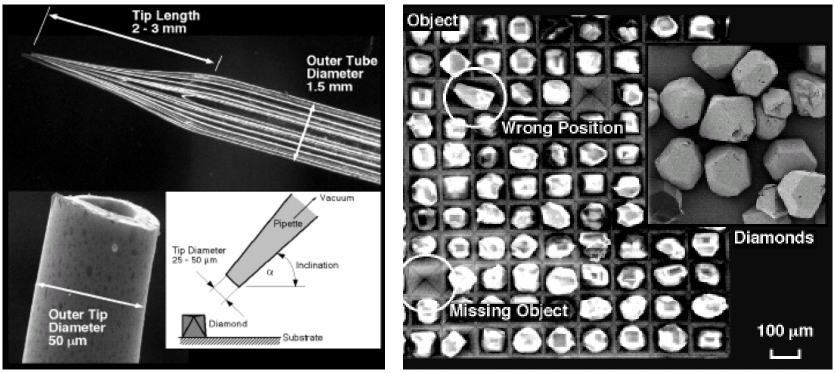


Figure 4-13 Glass pipette as a vacuum gripper & application case (Reparation of deposition defects)

At the Institute für Mikrotechnik Mainz GmbH (IMM), a vacuum gripper prototype for the assembly of optical fibre ribbons into MT-RJ a standard connector has been built for eight optical fibre ribbons [Ansel02]. The grip area is divided into two parts, two suction holes for the ribbon and eight suction holes, with 100 μm diameter, for each optical fibre. The positioning accuracy is ± 2 μm. The illustration and a detailed view of the suction holes are shown in Figure 4-14.

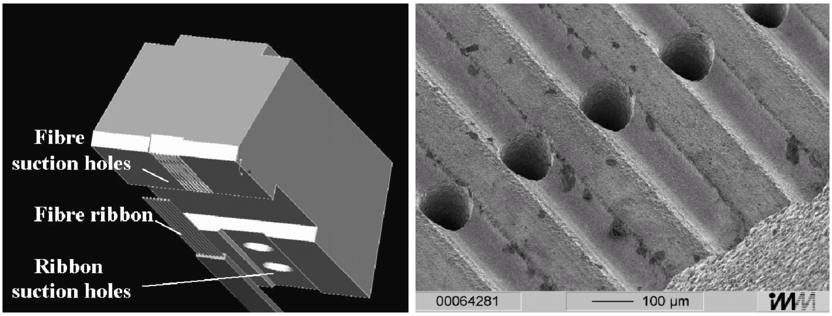


Figure 4-14 (left) A vacuum gripper for optical fibres batch handling (right) Details of the suction holes and grooves for fibres [Ansel02]

Pressure difference generated by thermal expansion: Negative pressure can also be generated by a temperature change. Such a gripper design is described in [Arai97]. In the tip of the gripper, there are several micro-holes fabricated onto the grip surface, as shown in Figure 4-15.

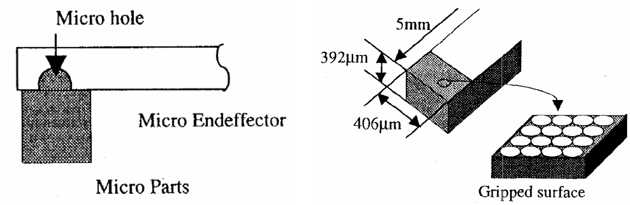


Figure 4-15 Principle of a vacuum gripper driven by thermal expansion [Arai97]

The gripper works in such a way that the temperature was increased until it was above room temperature in order to pick up a part. When contact with the part was made, the temperature of the gripper tip and in the micro-holes decreased. By this means, the pressure inside the holes became lower than the ambience pressure. The grip force is thus generated by the pressure difference. To release the object, the temperature of the gripper tip was increased again. Due to its small scale, the gripper has a reasonably short grip cycle time.

4.7 Electrostatic gripping

4.7.1 Grip principle and general design aspects

A charge difference between two particles causes a force of repulsion or attraction. In electrostatic gripping, this electric force field is used to operate target parts. The electrostatic force scales with the second power of the characteristic length, which makes it an interesting principle for gripping downscaled objects. Electrostatic gripping is more extensively researched in Section 5.7.

The electrostatic grip principle shows both advantages and disadvantages in applications. The grip force is generated by voltage difference (charge difference) between the gripper and the target component. The force can be rather conveniently controlled by adjusting the voltage applied to the gripper, which potentially ensures the principle for a large working range. However, this grip principle may leave some residue charges on the component after the operation. Damage can be done to certain electrically sensitive components. In case the residual charges cannot be properly cleaned after gripping, extra adhesion forces will be generated, which can disturb follow-up operations. This principle has been demonstrated in different designs for specific cases.

Releasing is normally done by alternating the voltage potential of the gripper, and if necessary, electrical potential can be added to a substrate when the part is released [Lang06-1], [Enikov04], [Saito03]. Another releasing strategy that works for this grip principle is to change the contact area or the contact angle [Tsuchiya99], [Saito01].

4.7.2 Actuation principles

Electrostatic micro-gripper with DC voltage: A gripper design is shown in [Enikov04]. The developed electrostatic micro-gripper utilizes aluminosilicate glass slides, coated with an Indium-Tin-Oxide (ITO) layer with a thickness of 160 Å–200 Å as the initial substrate. The ITO layer has good electronic conductivity and is semi-transparent in the visible wavelengths.

The gripper, as shown in Figure 4-16, has a grip area of 2.4 mm by 1.6 mm, and the filling ratio of the electrodes was 75%. A grip force of approximately 1.14 mN was measured under 200 V, according to [Enikov04].

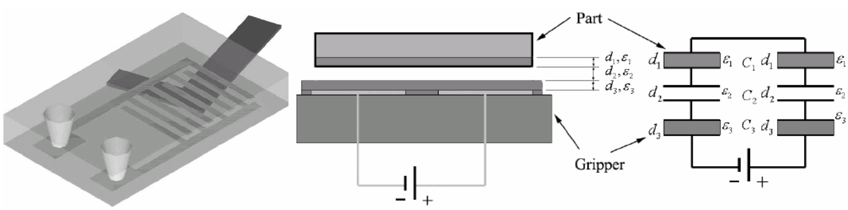


Figure 4-16 Electrostatic gripper and its equivalent circuit [Enikov04]

Gripping under scanning electron microscope: One remarkable feature of the Scanning Electron Microscope (SEM) observation environment is its electron beam injection. Objects that are exposed to the observation field are charged, [Miyazaki97]. The electrostatic force caused by the charge difference is far greater than the gravity of the object. Thus, electrostatic gripping can be performed under the SEM observation and has been reported in [Kasaya99], [Tsuchiya99], [Saito01].

4.8 Capillary force based gripping

The capillary force caused by the capillary effect has been addressed in many research topics [Torii93], [Bark98], [Grutzeck02], [Lambert03-1], [Schmid06]. As described in Chapter 1, the capillary force is the sum of the so-called tension force, F_T, and Laplace force, F_L, [Lambert05]. The overall capillary (surface tension) force is described as:

$$F_S = F_T + F_L = 2\pi r\gamma \sin\theta + \pi r^2 \gamma\left(\frac{1}{\rho_\perp} - \frac{1}{\rho_{//}}\right) \tag{4-2}$$

With r as the radius of the contact area, γ as the surface tension, and θ as the contact angle of liquid to solid. The $\rho_{//}$ and $\rho_\perp$ are the principle radii of the meniscus in the horizontal plane and the vertical plane, respectively. By knowing the geometry of the liquid meniscus, this capillary force can be calculated.

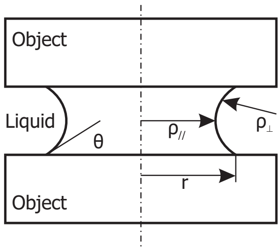


Figure 4-17 Capillary force calculation in the case of two parallel plates

The capillary force can also be estimated in a simpler method with approximations. It assumes that the two objects have the separation distance δ. The force can be described as [Lambert05]:

$$F_S = \frac{2\pi\gamma}{\delta}(r^2 \cos\theta + r\delta) \tag{4-3}$$

There are numerous release strategies for this grip principle. These include the application of acceleration to the gripping tool, changing the adhesion property of the liquid by means of electrowetting [Lambert05], or changing the contact area by adjusting the shape of the gripping tool [Biganzoli05].

Different kinds of liquids are adopted as the gripping intermediates in research studies, including water, silicon oil [Lambert05], and other low viscosity fluids. Applications that use the capillary grip principle, with low viscosity fluids to handle parts are reported in [Bark98]. Gripper design and the operation strategy are shown in Figure 4-18. On the basis of the experimental results, parts with different dimensions were picked up. The positioning accuracies of capillary force based grippers vary, subject to the match between the dimension of the gripper tip and the part. The grip principle offers the following characteristics:

- Centring effect of the part, due to the geometrical matching of the gripping interfaces;
- Compliance in part positioning and joining;
- Low and adjustable grip forces for handling fragile parts.

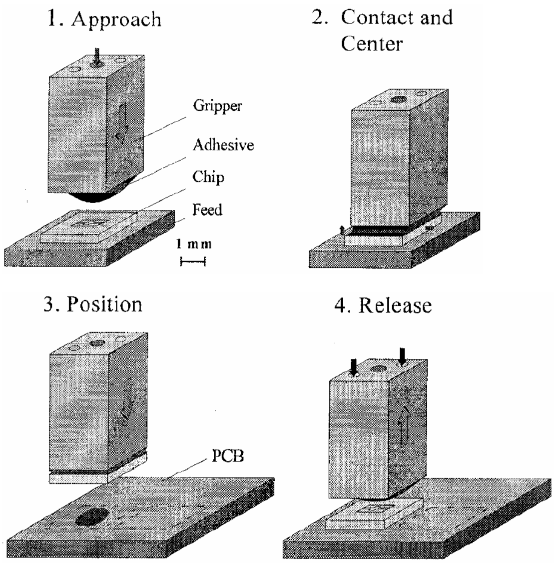


Figure 4-18 Gripping strategy with low viscosity fluids [Bark98]

4.9 Gripping on the basis of Van der Waals force

Van der Waals force is ever present. It shows some application potential in micro-scale gripping. As a possible grip principle, some research has been carried out, [Koyano96], [Feddema01], [Haliyo01]. Although the force becomes more noticeable in the micro-domain, it is rarely used individually for gripping an object. From another aspect in a part handling operation, the VDW force is difficult to separate from other adhesions. Consequently, the VDW force mainly represents one of the force components of the overall grip force. Nevertheless, VDW force based gripping will be used as the name to represent this principle.

A successful gripping operation with VDW force is only applicable for a small range of parts. The force magnitude is highly dependent upon the separation distance from the gripper to the target part and the surface roughness of the contact interface. The physical model has been described in Section 1.3. The force becomes significant in gripping parts with smooth surfaces with diameters of less than 200 micrometres.

Figure 4-19 shows one strategy described in [Feddema01] for picking and releasing particles using VDW force. In the figure, F_g is the force of gravity, F_{sa} is the force of surface attraction, and F_{ta} is the force of tool attraction.

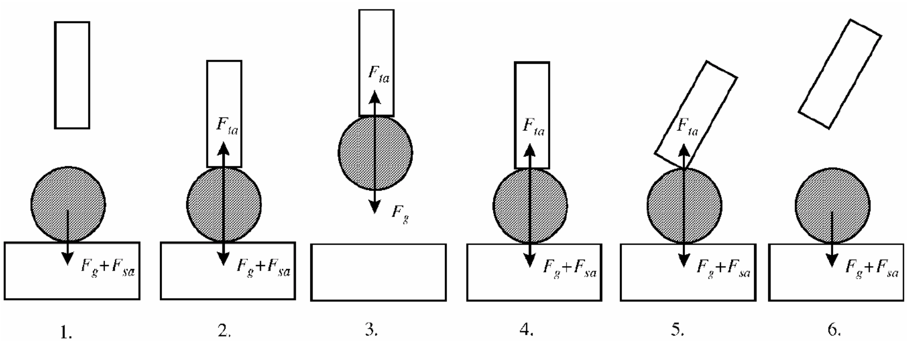


Figure 4-19 Pick up and release of a sphere with a flat-tipped tool, assuming VDW forces and no electrostatic forces [Feddema01]

4.10 Liquid solidification gripping (Cryogenic gripping)

In Part II of this thesis, liquid solidification based gripping is extensively researched. Liquid solidification based gripping works due to the fact that the adhesion force of certain liquids in their solid phase is much higher than in their liquid phase. By transforming the liquid gripping intermediate to its solid phases, a sufficient grip force can be generated. The principle applied a liquid, usually water, as a gripping intermediate, [Lang06-2]. This principle is also called Cryogenic gripping or freezing based gripping.

Releasing a component can be done by heating the gripping contact. When the gripping intermediate melts, the part can drop off by its gravity. In some cases, an auxiliary tool is employed in addition to heating up the intermediate in order to release the component [Patent EP 1319613A1].

A freezing based gripper prototype has been demonstrated by CSEM, the Swiss Center for Electronics and Microtechnology. A grip force of approximately 1 N/mm^2 was realized. The gripper achieved its operation of 400 cycles per hour, and could be used to pick up small components, measuring between 0.1 mm to 5 mm, [Kochan97]. The gripper is shown in Figure 4-20.

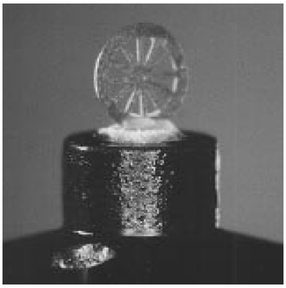


Figure 4-20 Freezing based gripper, demonstrated by CSEM, from [Kochan97]

4.11 Ultrasonic pressure gripping

As early as the 1970s, NASA and ESA, the two space organizations, began research into so-called "acoustic levitators". As achieved in the research, small solid and liquid objects were levitated without contact.

High-intensity ultrasonic energy offers a promising principle for non-contact handling of fragile and surface sensitive parts, such as wafers and substrates. It allows for precision gripping of parts with any geometries, material or dimensions from micrometre to meso-scale parts.

Two approaches are mainly addressed in the field of research. The operation can be effected by means of the sound radiation pressure of a standing wave, combined with a Bernoulli vacuum component [Reinhart00]. Another approach in using the acoustic pressure is Squeeze Film Levitation, or near field levitation, as referred to by several authors. As described in [Lambert04], the reflector of the standing wave levitation is replaced by the levitated object. Consequently, any weight can be levitated if the separation distance between the object and the vibrating plate is small enough. Examples can be seen in [Gao99], [Coakley00] and [Zäh02]. The schematic structure of the system is shown in Figure 4-21.

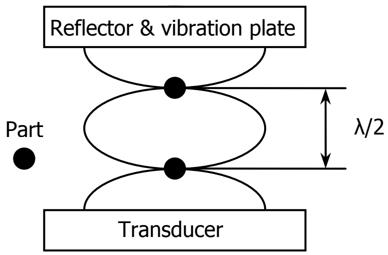


Figure 4-21 Radiation pressure of standing waves and particle levitation

4.12 Magnetism based gripping

A magnet can act a force interaction on the material being magnetised. Magnetic force arises from electrically charged particles in motion. This motion can either be the movement of electrons in an electric current, resulting in "electromagnetism", or the quantum-mechanical spin and orbital motion of electrons, resulting in permanent magnets.

Using magnetism based gripping devices for micro-handling is principally possible, however, the limitations are obvious. Although this force is used for gripping operations for the macro-dimensional objects, (e.g. handling bulk steel material or lifting trashed vehicles), when scaling from the macro to the micro-domain, it is clear that the scaling factor of the magnetic force is third or fourth power to the characteristic length, [Trimmer89]. This means that the magnetic force decreases more rapidly than gravity. Thus, the magnetic force is generally less interest to be used directly as a grip force in micro-gripping. The range of materials that can be manipulated with magnetism based grippers is limited. Only ferromagnetic material can be gripped. There are no application examples found in the literature studies.

Despite the limitations mentioned above, magnetism based micro-gripping could be used for handling meso-scale ferromagnetic parts. The grip principle is not sensitive to part geometries, and only one free surface is required to establish the grip force.

4.13 Optical pressure gripping

Pressure produced by a light source can levitate micro-objects. This optical pressure can be used as a grip principle. This principle is also known as optical trap. Two application schemes are approached for gripping operations.

First, levitation can be realized by approaching the micro-object from its top. Due to both beam reflection and refraction, the component undergoes an axial force that always pushes it forwards in the direction of the beam, and a radial gradient force that traps it in the centre of the beam when its refractive index is higher than that of the surrounding medium (water, oil, air, etc.) [Lambert04]. As reported in [Ashkin86], a 10 μm glass sphere was trapped and levitated in a laser beam focus of 100 mW, with water as the operational environment. The operation concept is shown in Figure 4-22. Further information can be found in [Bancel99], [Fukuda00].

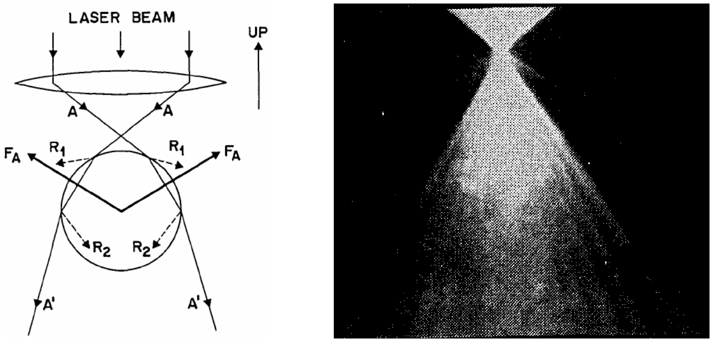


Figure 4-22 (Left) Diagram shows the ray optics of a spherical particle trapped by the highly convergent light of a single-beam gradient force trap. (Right) a 10 μm sphere is trapped in light, showing the paths of the incident and scattered light rays, operation done in water. [Ashkin86]

The second method of gripping parts with this principle is by illuminating a micro-part from the bottom. The part is then confined to the beam centre by transverse gradient forces, but propelled along in the direction of the beam propagation by radiation pressure forces as described in [Bancel98].

The principle is widely used in handling biological particles. One of the most important advantages of optical pressure gripping is permitting contactless manipulation. Extremely sensitive particles (*e.g.* live cells) can be manipulated with less overt damage.

4.14 Gripping on the basis of the Bernoulli Effect

The Bernoulli Effect describes the dynamic pressure behaviour of fluids. The pressure is lower in the region where the flow velocity of a fluid is increased. An increase in the velocity of air flow between the gripper tip surface and the part interaction surface will result in a decrease in the pressure; by this means, a part can be picked up [Grutzeck02]. The schematic drawing of a Bernoulli Effect based gripper is shown in Figure 4-23. In order to create this attracting force, the clearance gap of a nozzle must be small enough in comparison to the diameter of the central air inlet, and the radial distance through which the air flows. The gap between the gripper and micro-part is, to some extent, self-regulating and creates local stiffness, which is favourable during the manipulation of non-rigid parts. Auto-centring can be generated by the dynamic pressure of the air flow. The equation of grip force F_B can be written with the radius of the air inlet (r') and the radius of the force interaction surface I, the velocity of air flow (V) and air density ρ_{air} :

$$F_B = -\pi r^2 V^2 \ln(\frac{r'}{r})\rho_{air} \tag{4-4}$$

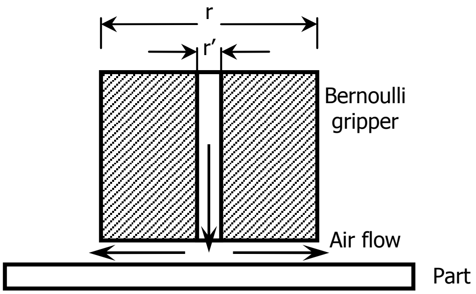


Figure 4-23 Bernoulli gripper and the force measurement

This grip principle is one of the ideal solutions if non-contact handling is desired to prevent bruising or contamination. The auto-centring feature of the gripping method is valuable for many part handling operations, which is beneficial for maintaining the gripping accuracy. Flat, non-rigid, symmetric and two dimensional (thin) parts can easily be gripped by this principle. A grip force of approximately 5 mN is measured for picking up a 4 mm sized part with a 0.2 mm diameter air inlet.

4.15 Conclusions

A review of gripping methods is undertaken according to their physical principles. A total of 11 different principles is distinguished and addressed in this chapter. On the basis of the analysis of the gripping process, the characteristics of micro-gripping are identified and used in reviewing each individual grip principles.

From the review, the following points can be summarized:

- The understanding of different grip principles is not developed in comparable extents. Friction gripping and vacuum gripping are better researched on the principle level and further developed on the application level. In comparison, other principles (*e.g.* ultrasonic pressure gripping and liquid solidification) are less often addressed in research. Knowledge is not widely available on either the principle level or on the application aspects.
- The application fields addressed by individual gripping methods are rather specific. Although particular cases are used in demonstrating a gripping method, the capabilities or limitations of the grip principle remain unclear on a more general level. The applicability of a principle is not clearly understood in terms of well-defined parameters.
- Diverse methods and criteria are adopted in each research activity to describe the capability of a gripping method or principle. Thus, the general performance of the grip principles cannot be easily compared to each other. Meanwhile, the knowledge gained from individual gripping implementations is not easily

transferable from one application to another, due to the lack of knowledge compatibility.

It can be concluded that there is a strong need for a methodology, a framework which can structure the critical issues of gripping technologies, allows for systematic understanding on all principles, and provides a guideline in gripping method selection.

The definition and parameters of such a framework are described in Chapter 5. The information described in Chapter 4 served as the groundwork for the establishment of this framework.

5 The framework of micro-gripping technologies

On the basis of the technology review described in Chapter 4, it is obvious that many physical principles are explored as micro-grip principles. The knowledge of micro-gripping is garnered in both theoretical and application aspects. However, what is lacking in this field is a systematic understanding of the critical common issues regarding the micro-gripping technologies, which bridge the understanding of the physical principles and knowledge needed for applications. These issues are related not only to the characteristics of the physical mechanism of gripping, but also to the diverse technologies of the assembly process, application environment, and economical aspects.

This research work proposes a framework for gripping knowledge, which tackles the issues mentioned above. The framework covers both principle related understanding, (*e.g.* force mechanism and dominating parameters), and process related knowledge, (*e.g.* the flexibility in applications). Given the fact that the gripping operation is a sub-process of an assembly activity and the general development of the gripping technology eventually has the goal of being implemented into applications, the criteria for the framework are selected and defined on the basis of systematic analysis in the micro-assembly process, micro-gripping process, and other relevant aspects. The framework provides a guideline to understanding the features of micro-grip principles, and for preliminary selection of grip principles with respect to specific applications.

The information and data contained in this framework are collected from both literature studies and the studies done in this research project. More specifically, the electrostatic gripping and liquid solidification gripping are the topics of this research project. The results of the study of these two grip principles contribute to the completion of the framework. The research on electrostatic gripping is presented in this chapter.

The framework can be presented in different forms, subject to the purpose. For instance, a table layout can be used to make comparisons between principles, or as a process data sheet, which summarizes the process window of each grip principle. Although the framework is suitable to classify all grip principles, only a selected number of principles are included in the form of process data sheet in this chapter. In examining the features of each principle and their application capabilities, only the principles with strong application potential are presented in the following sections. These are friction, form closure, vacuum, electrostatic, capillary (*i.e.* surface tension), and liquid solidification, as shown in Figure 5-1.

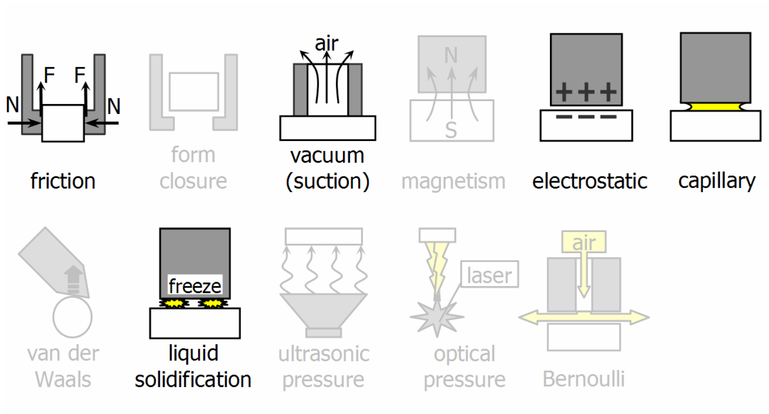


Figure 5-1 The five grip principles included in the data sheet (friction, form closure, vacuum, electrostatic, capillary)

The process of defining the framework begins at the level of analyzing the general assembly process, addressed in Section 5.1. Section 5.2 describes the analysis of the gripping process. On the basis of this analysis, the criteria are determined, and the framework is defined. The entire framework of gripping technology is given in Section 5.3. In Section 5.4 an illustration case is presented to describe one of the possible uses of the framework. Following that, the framework is applied to five pre-selected grip principles. As a result, the process window of each of these five grip principles is concluded in individual sections from 5.5 to 5.10. The research on electrostatic gripping is reported in Section 5.7, where modelling and experimental works are addressed. The summary of the chapter is given in Section 5.11.

5.1 General framework with respect to assembly

The definition of the framework begins with an examination of the general aspects of assembly process. The technological relationship between products and the assembly process is illustrated. In describing this relationship, the assembly characteristics of the products need to be understood [Tichem06]. This is shown in Figure 5-2.

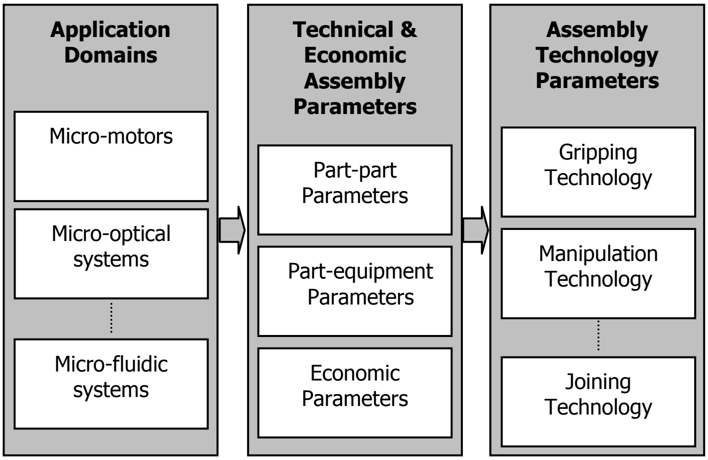


Figure 5-2 General framework for technology identification

On the left-hand side, classes of products are shown from an application perspective. However, the listing and descriptions on the level of application domains do not allow for defining relationships with respect to the required assembly technologies. In order to do so, the technical and economic parameters, which are decisive for the assembly technology, must be selected. These technical and economic parameters are represented in the centre column of the figure. Obviously, there is no unique, direct relationship between the three columns of parameters. Rather, the relevance of the framework in this level is to clarify the thinking patterns in translating product characteristics into required assembly techniques.

The most important relationships to be described exist between the column of technical and economic parameters (the centre column), and the column of assembly technology (the right column). Three main classes of part parameters are identified:

- Part-to-part parameters;
- Part-to-equipment parameters; and
- Production economic parameters.

The essence of assembly is to bring together parts into a joined state. The parameters of the part-to-part relationships to be established will therefore be one of the main classes of parameters, which determine the technology. Within this category, this could consist of parameters such as the positioning accuracy at the place where parts are to be joined. This is related to manipulation techniques and the application of sensor systems, and the material combinations that need to be joined. This, in turn, is related to the joining techniques that can be applied.

The second category, part-to-equipment parameters, highlights another main aspect of assembly. In establishing part relations, the parts are being handled by equipment. In assembly, particularly in the field of mechanical products, this poses a major challenge, as the interface between the equipment and the parts to be handled is not standardised. Part parameters that influence the selection of handling technology or handling equipment are contained in this category.

Finally, the third category, production economic parameters, defines the production economic conditions that must be met by the assembly process in terms of production volumes and the variety of products to be assembled.

5.2 Defined criteria

This section details the general framework depicted in Figure 5-2 and defines the relevant parameters with the focus on technology for micro-part gripping, [Tichem06].

5.2.1 Technical parameters

The first main category of technical parameters is defined by the part-to-part relationship to be established during assembly. A parameter of micro-gripping is the *accuracy*, which is to be established during assembly. However, the position accuracy of the part with respect to the gripping device is only one element in the tolerance chain that determines the final joining accuracy, and it may not be the decisive one for the required accuracy. Generally speaking, accuracy is either obtained through manufacturing (i.e. the accuracy is in the parts/products, a passive alignment scheme is applied) or through assembly (i.e. the execution of the assembly process is decisive for the final part position). In the first case, a maximum requirement on the part-gripping device error may be specified to correctly execute a certain passive alignment scheme. In the second case, if the part-gripping device relationship error exceeds an allowable limit, additional sensor measurements may be necessary to register the position of the part with respect to the gripping device, or the position of the part with respect to any other coordinate frame in the environment. Performing additional sensor measurements may relieve the demand on the accuracy in the part-gripper relationship. In conclusion, the **accuracy performance** is a parameter that needs to be considered in selecting a gripping solution. Having stated this, there are numerous conditions that must be taken into account to explain the relation to gripping technology.

The definition of gripping is identified as the essence of gripping, which is a kinematic relationship that is secured by a force interaction between the gripping device and the part to be gripped. This allows for a definition of a number of part-equipment related parameters relevant to micro-gripping.

Firstly, the gripping device must apply a force or load on the part so that the part can be lifted, moved and joined. During this process, various forces may act on the part. The force interaction surface is defined as that portion of the part's surface through which the grip force (field) operates. Therefore, the first parameter to be defined is the *available force interaction surface*. This parameter is related to the ability of the gripping solution to create a force (field) of sufficient load per unit area of contact. This is referred to as the magnitude of **the specific grip force (field)**.

The available force interaction surface is that portion of the total part area which remains after subtracting those surfaces which are not accessible by the force (field). From the perspective of mechanical interaction, inaccessibility of surfaces may be due to the way the part is being presented to the gripper in the part feeding stage, and to the way the part is assembled.

From a more general perspective, a grip principle may require the interaction surface or part to have certain properties to be handled. It can be surmised that a Bernoulli Effect based gripper has more difficulty in gripping a hollow-shaped part. As another example, IC chips may not be handled by an electrostatic based gripping device due to the electrostatic sensitivity of the chips. Furthermore, certain surfaces may not be allowed to be contacted, due to the possibility of causing a certain type of damage to the surface, which is not allowed for functional reasons, (*e.g.* scratches on optical surfaces). The aspect of damageability is discussed later in this section.

A more detailed analysis of the interaction between the gripping device and the part shows that it is not only the total force interaction surface that is relevant, but also the *configuration of force interaction surfaces*. This second parameter is related to the requirement of a grip principle to apply the force or load on the part through a **number of contact surfaces with a certain configuration**. In particular, the friction based grip principle requires at least two surfaces to contact the part.

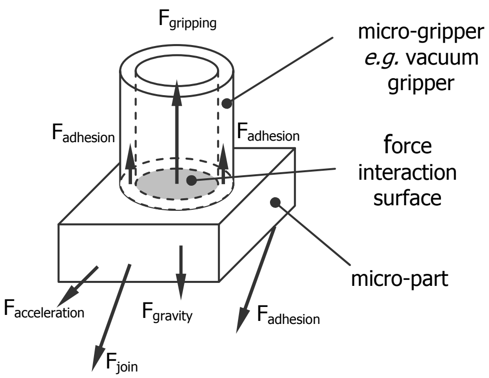


Figure 5-3 Forces operating on the part
(In the example shown, there is only one force interaction surface.)

Secondly, while a kinematic relationship is established between a part and gripping device, other forces may impose upon the part. See Figure 5-3. Acceleration forces and adhesive forces from the environment may play a role in the entire gripping process. In particular, however, the forces that may occur during joining of the parts need to be considered. This may happen in those cases where the part needs to be held while the joining process is executed. These forces are labelled as *assembly forces* during handling. This parameter is related to two factors. Firstly, the stiffness of the gripping connection, and secondly, whether or not the grip force is retainable where the relative position of the part to the gripper is slightly shifted. The **grip stiffness and retainability** must be investigated in all directions of the operating force interactions.

Thirdly, the force(s) (fields) that impose upon a part may cause damage to it. The chance of causing damage (the *damageability* of the part) is related to the properties of the part, *e.g.* the material and function, and to the grip force (field) applied to it, *e.g.* the nature of the force and the strength. The list of grip principles clarifies that various force fields and possible causes of damage may be present, including mechanical forces, electrostatic force fields, and liquid interaction, which are labelled as **damage causes**. However, it is difficult to quantify damageability. This criterion is specified as scratch, deformation, thermal interference, surface contamination (residue or imprint), and inductive interference. A finger-based gripper may introduce some elastic or even plastic deformation of the part. Whether this is acceptable or not can only be determined if a detailed investigation is done on the sensitivity of the successful execution of the assembly process, and the products functional performance, given such damages.

5.2.2 Economic parameters

There are numerous economic parameters which are relevant to the gripping process, including demands, throughput, reliability, durability, investment, energy consumption, *etc*. However, in examining state-of-the-art research in gripping technology, not all of these parameters can be taken into account. Furthermore, some of these parameters are rather case-specific. In this section, two production economic criteria are illustrated with respect to the selection of gripping solutions. These are the *diversity of products and components* to be handled by one gripper, and the *production volume, i.e. the number of products*, to be assembled per unit of time.

In itself, product and part diversity are not sufficiently defined parameters for selecting gripping technology. During the design of the assembly system, assembly tasks will be allocated to resources. This defines whether or not there is a demand for **gripper flexibility**. Flexibility has various aspects, and in the context of this discussion it is used to refer to its ability to handle more than one type of part with the same gripper, without exchange of fingers or other parts of the gripper. This can also be referred to as versatility. The flexibility of a gripping solution can be translated into other parameters, such as the need for having more than one contact point/force interaction surface, and the range of force levels that can be delivered. Additional parameters include the need for shape correspondence in the interface between the gripping device and the part (the force interaction surface), and the (dis)ability to handle certain material types (*e.g.*

magnetic based gripping devices). With respect to an assembly process wherein a certain grip principle applies, the flexibility refers to the compatibility of a grip principle with the assembly process and the manufacturing environment. For instance, the humidity, vacuum, electric field intensity and temperature conditions or requirements of an operational environment have a strong influence on the selection of the grip principle and actuation principle. For example, a gripping device based on electrostatic force, will introduce an electric field into the environment and thus, it may not be used in an electrostatically sensitive environment. Flexibility is detailed in three aspects, which are (1) geometry related, (2) material and function related, and (3) process related.

The second parameter is the *production volume*. This parameter is important for estimating the execution time of each manufacturing process. The number of tasks that are allocated to one gripper per unit of time is the criterion which decides the required **grip cycle time**. The grip cycle time is defined as the time needed for establishing and ending the kinematic relationship between the gripping device and the part to be gripped, without the intermediate move operation.

5.2.3 Overview of all parameters for the framework

Figure 5-4 shows the framework with all parameters.

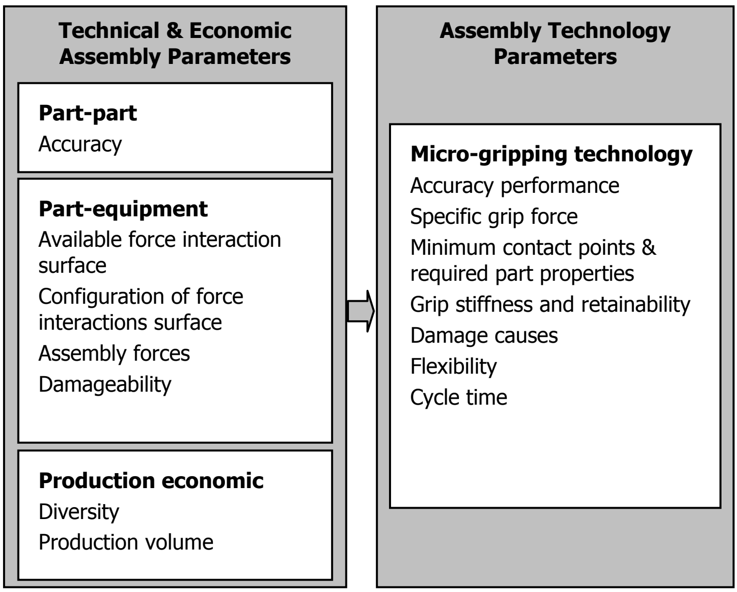


Figure 5-4 Detailed general framework for grip
(Technical and economic parameters are highlighted with *Italic* font and assembly technology parameters are highlighted with **Bold** font in the text)

Although some of the parameters are quantifiable, others may only be described in a qualitative way. A framework completed with data is presented in the next section of this chapter. It should be noted that in some cases actual data also depends on the design of the gripper, and the data for some of the parameters shown should only be considered as indications of ranges that can be expected. Even so, it can be concluded that, in principle, qualitative or quantitative values can be assigned to each of the parameters.

5.3 The defined framework

On the basis of the set of criteria defined in Section 5.2, the framework for micro-gripping can be concluded as set out in Table 5-1, Table 5-2, and Table 5-3. The information contained in the tables is summarized from the literature surveys presented in Chapter 4 and from the research results of this project.

Table 5-1 The framework of micro-gripping (part 1)

Principles	Force parameters	Accuracy performance	(Specific) grip force
Friction	$F_{grip} = f(N, \mu)$ N: the normal force μ: friction coefficient	Relatively high to high accuracy. Influencing factors: adhesion between gripper fingers and the part, asymmetrical fingers movements. Fine positioning is feasible with individual finger movement, subject to designs.	The actual grip force depends upon the specific actuation principle and the design of gripper mechanism, (*e.g.* the gear ratio and stiffness of the gripper jaws). Typical value: micro-Newton to Newton.
Vacuum	$F_{grip} = f(\Delta P, A)$ *ΔP*: pressure difference *A*: grip area	Very high accuracy. Influencing factors: adhesion and uneven force distribution in release, *e.g.* by blowing the part away.	The actual vacuum in handling an application is in the range of 50 Kpa to 80 Kpa, which produces the specific grip force of between 0.5 – 0.8 mN/mm^2.
Electrostatic	$F_{grip} = f(A, \varepsilon_r, \delta, U)$ *A*: grip area ε_r: relative permittivity *δ:* separation distance *U:* voltage	Relatively high accuracy. Influencing factor: gripper design. The accuracy depends upon the pattern of the electrodes and the matching with the geometry of the part.	The typical value of the specific grip force is in the range of mN/mm^2, under a few hundreds Volt potential difference.
Surface tension	$F_{grip} = f(\gamma, \delta, V, \theta)$ *γ* : surface tension *δ* : separation distance *V*: liquid volume *θ:* contact angle	High accuracy in handling geometrical symmetric parts. Parts tend to orientate and couple with the shape of the gripping contact area. Influencing factors: geometrical accuracy of parts, force distribution in release, *e.g.* acceleration.	The typical value of the grip force is in the range of a few milli-Newtons, with 1 μL water applied as the gripping intermediate.
Liquid solidification	Grip force depends upon: the material of part, gripper and liquid; surface roughness; gripping temperature.	Relatively high accuracy. Influencing factors: force change and position change due to the phase transformation.	Specific grip force approximately 1 N/mm^2.

Principles	Damage causes	Flexibility
Friction	Possible damages: scratch, deformation	**Geometry related**: typical part size: sub-millimetre to millimetres / fits for most geometries / suitable for limited geometry diversities / difficult to handle thin film or fine mechanical structure. **Material and function related**: contact restriction on functional surfaces / caution in handling fragile part / sensitive to adhesion. **Process related**: not suitable where there is limited working space around the part.
Vacuum	Possible damages: scratch	**Geometry related**: typical part size: few tens of micrometres to millimetres / fits for small unsymmetrical / suitable for large geometry diversities / difficult to handle open structure. **Material and function related**: caution in contacting functional surfaces / not suitable for handling porous or loose materials. **Process related**: grip force decreases in low pressure environment / caution: gripper nozzle clogging.
Electrostatic	Possible damages: inductive interference	**Geometry related**: typical part size: few micrometres to millimetres / fits for most geometries / suitable for large geometry diversities / caution: a change of geometries may vary the accuracy. **Material and function related**: suitable for both conductive and non-conductive materials / possible grip on functional surfaces / not for electrically sensitive parts. **Process related**: caution: grip force may decrease when contacting conductive objects during gripping / possible inductive interference to the assembly environment.
Surface tension	Possible damages : surface contamination (residue or imprint)	**Geometry related**: typical part size: few tens of micrometres to millimetres / fits for very small unsymmetrical / fit for small geometry diversities / not suitable for open structure or hollow shape. **Material and function related**: possible grip on functional surfaces / not suitable for hydrophobic or absorbent surfaces / caution: possible surface contamination. **Process related**: caution: very low grip stiffness (part floats under the gripper).
Liquid solidification	Possible damages: surface contamination (residue or imprint), thermal interference	**Geometry related**: typical part size: sub-millimetre to millimetres / fits for most geometries including large unsymmetrical / suitable for very large geometrical diversities. **Material and function related**: possible grip on functional surfaces in most cases / not suitable for hydrophobic surfaces. **Process related**: caution: temperature change / caution: possible local condensation.

Table 5-2 The framework of micro-gripping (part 2)

Principles	Cycle time	Minimum contact points	Required part properties	Grip stiffness and retainability
Friction	Actuation principles dependent. Typical cycle time 0.01 s.	2 grip surfaces, on the opposite sides of a target part.	Sufficient grip surface area accessible from both sides. / Surface properties of the contact influences the grip force and release strategy.	Grip stiffness depends on the friction. / Grip force is retainable in all directions.
Vacuum	Typical cycle time in milliseconds or even shorter.	1 grip surface, in principle, can be at any angle.	Sufficient grip surface area close to the inertia centre. / Smooth, non-porous grip surface / Surface profile matching between the part and the gripper.	Grip stiffness depends on the friction. / Grip force is retainable along the grip surface.
Electrostatic	The typical cycle time in milliseconds or even shorter.	1 grip surface, normally on top.	Flat and smooth grip surface preferred, or, surface profile matching between the part and gripper. / Grip force diminishes by increasing the roughness of the contact.	Grip stiffness depends on the friction, drops due to discharging. / Grip force is retainable along the grip surface.
Surface tension	Typical cycle time in milliseconds.	1 grip surface, on top.	Sufficient grip surface area accessible from top, aligned to the inertia centre. / Grip surface should not be absorbent, hydrophobic or oleophobic.	Grip stiffness is very low in all directions, dependent upon the viscosity of the intermediate. / Grip force is retainable in all directions.
Liquid solidification	Typical cycle time in 4 – 9 s from literature survey. Minimum 0.1 s in this research.	1 grip surface, possible at any angle.	Grip surface should not be hydrophobic.	Grip stiffness is high in all directions, dependent upon temperature and the strength of the intermediate / Grip force is not retainable in any direction.

Table 5-3 The framework of micro-gripping (part 3)

5.4 Qualitative case illustration

To illustrate the framework and the parameters as defined in the previous section, an example of grip principle selection is qualitatively demonstrated.

Description of the application case

The part, a rectangular support frame, and its assembly process to transform it into a metal case, are shown in Figure 5-5, [Tichem06].

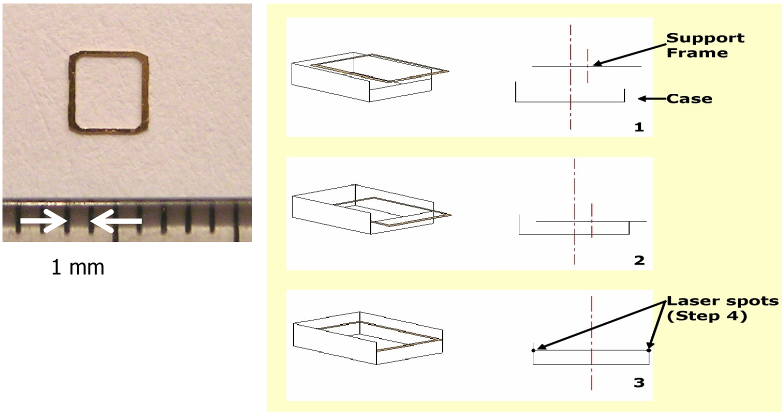


Figure 5-5 Component and its assembly process

In this assembly process, the support frame must be, (1) picked up, (2) positioned with respect to the case, and (3) subsequently joined by laser spot-welding. There are stringent position accuracy demands in this assembly process. The support frame must be kept and joined in position with respect to the case within a 4 μm tolerance. The gripper must hold the part during the joining operation, in which the assembly force exerted on the part may increase up to a few Newtons (4 N max).

Analysis of the assembly process

The support frames are composed of thin metal sheets (a few tens of micrometres thickness), and are presented to the assembly system in an ordered matrix structure. This very clearly simplifies feeding and picking of the individual parts. However, a consequence is that the only available areas for force interaction with the part are the inner geometry and the upper surface of the support frame. The upper surface is small, with the width of the "ring" in the order of 100 μm. In addition, the final assembly position of the support frame does not allow for force interaction in gripping through surfaces other than described above.

The assembly forces on the part are relatively large, approximately 4 N, as described above. At the moment the part is joined, the gripper must hold the part in an accurate position (tolerance 4 μm), defined in the direction perpendicular to the support frame in the position as shown in Figure 5-5. The gripper-part relation must withstand these high joining forces.

There is a definite possibility of mechanical damageability, given the small dimensions of the structure. If a force is operated on the inner geometry of the support frame, elastic deformation will take place. Whether or not this can be maintained at an acceptable level must be examined. Furthermore, electrostatic charging of the product is not allowed, and wherever possible, this must be prevented in assembly.

In this example, the production volumes are very high, in the range of millions per year. The gripper is expected to handle only this type of component. Therefore, the flexibility of the gripper is not important in this case, and the grip cycle time must be in the sub-second range. Table 5-4 summarizes the evaluation of the relevant assembly parameters for this case.

Technical & Economic Parameters	**Evaluations**
Available force interaction surface and configuration	Very small accessible contact area vs. large outer dimension. Hollow shape. Only inner and top surfaces accessible for gripping.
Assembly forces	High force, up to 4 N. (Laser spot-welding).
Damageability	Sensitive to both elastic and plastic deformation. Electrostatic charge not allowed in application.
Accuracy	High accuracy demand ~4 μm.
Diversity	One component type per gripper.
Production volume	Very high volume. Short grip cycle time ~1 part per second.

Table 5-4 Assembly parameters

Selection of the grip principle

The potentially high assembly force determines the applicability of a number of the grip principles mentioned. Electrostatic gripping is not desirable in this application, regardless of the force it can provide. Liquid solidification gripping may be a good option from the force perspective. However, current figures from literature on cycle time, as summarized in the process data sheets, do not permit application in high speed assembly. In conclusion, friction based gripping is an optimal option. Liquid solidification based gripping is a good alternative, however, grippers with considerably lower cycle times then need to be available. Table 5-5 shows the consequences of these parameter values for the grip principles discussed in this chapter.

Grip principles	Evaluations
Friction	Restricted space for gripper finger positioning. Mechanical damage to be considered.
Vacuum	Small contact area is available. High assembly force may cause a problem.
Electrostatic	Electrostatic force field is unwanted for this case. High assembly forces may cause a problem.
Surface tension	Gripper-part connection insufficiently stiff, which leads to accuracy problem.
Liquid solidification	Check grip force level. Grip cycle time is long.

Table 5-5 Observations of applicability of grip principles

The industrial situation in this case is as follows. The most widely used principles in industry, friction and form closure based grip principles, are hybridized in the gripper design. A gripper based on these two principles is implemented in the assembly process, especially for this component. However, the development of this solution involved a lengthy and extensive development path.

5.5 Process window for Friction gripping

Description, physical model and actuations

The typical gripper configuration, on the basis of this principle, is equipped with a pair of jaws, which can move towards the to-be-gripped object and make contact with it. As such, clamping forces are added to the contact surface. The maximum grip force is proportional to the sum of normal forces added to the surface and the friction coefficient of the grip surfaces. According to scaling laws, surface related forces can be a large portion of the normal force in handling miniaturized objects.

Different actuation principles can be used to enable the movement of gripper jaws. The commonly employed actuations are electrostatic actuation, electromagnetic actuation, SMA, pneumatic actuation, and piezo-actuation.

Configuration of grip

In general, the grip force depends upon the normal forces and the surface property, in which the normal forces include the possible adhesion between contact surfaces. The dependency of the grip force F_{grip} can be described as:

$$F_{grip} = f(N, \mu) \quad , \tag{5-1}$$

with N as the normal force and μ as the friction coefficient.

The actual grip force depends upon the specific actuation principle and the design of gripper mechanism, (*e.g.* the gear ratio and stiffness of the gripper jaws). The grip force has a typical value in the range of micro-Newtons to Newtons, subject to different actuation principles and designs.

A friction-based gripper requires at least two grip surfaces located on the opposite sides of a target part. The surface properties of the contact area influence the value of grip force and releasing possibilities.

The grip stiffness depends upon the gripper design. Generally, the stiffness is reasonably good, and can be adjusted by applying certain actuation principles in gripper design. Grip force is retainable in all directions against small shifts of the gripped object.

Accuracy performance

The accuracy performance of this principle is relatively good. Position repeatability is high. Fine positioning can be realized by moving each gripper finger individually. Major influencing factors on accuracy are adhesion between gripper fingers and the part, and asymmetrical finger movements.

Damage causes

The grip may plastically deform the part. The gripper may cause mechanical damage, such as scratches, to the functional surface of a part.

Flexibility

Geometry related: The principle fits most geometries. Parts with dimensions from a few hundred micrometres to millimetres can be handled. The principle requires at least two grip surfaces located on the opposite sides of a target part. A single gripper can handle different parts with limited geometry diversity. Thin, film shaped parts are difficult for this principle to handle in the case where such a part lays on a substrate with one surface fully inaccessible for the gripper.

Material and function related: Most engineering materials can be handled without problems. Gripping contact on functional surfaces of a part is restricted, due to possible damage to the part. This principle is relatively sensitive to adhesion. Due to this fact, the contact surfaces are often minimized in designing the gripping jaws. As a result, the contact pressure can be increased, which possibly impacts the contact surfaces or fine structures.

Process related: Grip force is established by means of physical contact. Thus, sufficient space around the part is needed to insert the gripper. One of the critical issues for this kind of gripping is how to eliminate the negative influence caused by adhesion force (sticking effect). Different kinds of add-on elements for the gripper or special structures on gripper fingers, are developed in order to reduce the adhesion forces that cause malfunctions when releasing a part.

Cycle time

The grip cycle time mainly depends upon the response time of the gripper actuators. For instance, electrostatic actuated grippers normally respond in a higher frequency than SMA-actuated grippers. The typical grip cycle time is in the order of 0.01 seconds.

Typical dimensions of operated objects and applications

A diverse range of objects with a large dimensional variety can be handled, including glass fibres and mechanical components in the range of a few micro-metres to millimetres.

5.6 Process window for vacuum gripping

Description and physical model and actuation

Vacuum gripping works on the basis of the pressure difference between the grip area and ambience. This principle is also known as suction-based gripping. The grip force is proportional to the size of the grip area, which makes the principles interesting for micro-parts handling.

The pressure difference is commonly generated by an external pneumatic pump. Other principles, such as expending the space of a closed cavity, are also applied.

Configuration of grip

The grip force can be expressed as:

$$F_{grip} = f(\Delta P, A), \qquad (5\text{-}2)$$

with ΔP as the pressure difference and A as grip force interaction area.

The theoretical pressure difference for operations performed in an open environment, *i.e.* without ambience pressure control, is a maximum of 1 bar, 100 Kpa. However, the actual vacuum that can be achieved in application is in the range of 50 Kpa to 80 Kpa, which produces the specific grip force of between 0.5 mN/mm^2 to 0.8 mN/mm^2.

This process requires a minimum of one grip surface on the target object, which in principle, can be at any angle. A smooth and non-porous surface is preferred for higher grip force. The surface profile of the object must match the profile of the gripper nozzle in order to close the air flow and generate enough grip force. In certain applications, this issue is approached by covering the gripper contact surface with a compliant layer.

The grip stiffness is limited, due to the maximum pressure difference and accessible surface area for gripping. The grip force is easily controllable in its working range by changing the pressure differential. Grip force is retainable only along the grip surface against small shifts of the gripped object.

Accuracy performance

The principle delivers very high accuracy in the gripping operation. Position repeatability is high. Influencing factors on accuracy include adhesion and uneven force distribution in the release action, (*e.g.* releasing a part by blowing can increase the positioning error).

Damage causes

Gripping on a functional surface, for example an optical surface, can cause scratches.

Flexibility

Geometry related: The principle fits for most geometries. Parts with dimensions from a few tens of micrometres to millimetres can be handled. The principle requires a minimum of one grip surface. It is suitable for handling small unsymmetrical objects. As long as a smooth surface is presented for gripper access, the gripping can proceed. It is possible to apply a single gripper to different types of parts in large diversity. However, open structures, heavy or off-centred parts may cause problems in applying this principle.

Material and function related: The principle can handle most engineering materials. Parts made from porous or loose material may result in a small grip force or no grip force, due to leakage. Set up of the gripping contact on the functional surfaces of a part is not suggested in certain situations due to the fact that it may scratch the surface.

Process related: The grip force is established by means of a pressure differential, which allows building grippers to have smaller footprints than target parts. Gripping can proceed in a limited work space. The grip force, in principle, is limited. Handling can be difficult in the case of target parts with small grip areas against large gravity (inertia), or small grip areas against a large assembly force. The grip force decreases where the handling takes place in a low pressure environment. Clogging can be a problem for grippers with small nozzles, which is known to occur in industrial implementations.

Cycle time

The cycle time of vacuum gripping can be very short, and depends upon the time to generate sufficient pressure difference at gripper nozzle. For a well developed system, the typical cycle is in the order of 0.01 seconds, or even shorter.

Typical dimensions of operated objects and applications

Parts with dimensions from a few tens of micrometres to a few millimetres are handled with this principle. The principle is widely implemented in pick-and-place diverse electric components. For example, in printed circuit board assembly processes, electronic components with sizes as small as 0.25 mm by 0.12 mm are handled with vacuum grippers. In other pick and place applications, (*e.g.* packaging small components and assembling mechanical parts), this principle is also often used.

5.7 Modelling and experimental study of electrostatic gripping

Some developmental results for electrostatic gripping are collected from known literature. However, the information is not sufficient to draw a process window for the electrostatic grip principle. A better understanding of the features of the gripping method with regard to its application performance and capabilities is still important. For this purpose, a computer model and a test bench are built to investigate the gripping environment and process related features. By combining the results of this research and the literature survey, the process window of electrostatic gripping is discussed in Section 5.8.

5.7.1 Electrostatic interaction

For two charged particles, A and B, in an electric field, the induced electrostatic force, based on Coulomb's Law, can be expressed as:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{qq'}{\delta^2}, \tag{5-3}$$

with δ as the distance between the two charged particles in the field and ε_0 as the permittivity of free space (vacuum) and has the value:

$$\varepsilon_0 = 8.854 \times 10^{-12}. \tag{5-4}$$

The force F is repulsive if both charges, q and q', carry positive or negative charges, or attractive, if the two charges have opposite signs.

Electrostatic forces in parallel plates can be described as follows. Figure 5-6 represents two charged plates separated by a dielectric material (i.e., an electrically insulating material) with a gap δ. The plates become electrically charged when an electromotive force (emf), or voltage, is applied to the plates. This action will induce capacitance I in the charged plates, which can be expressed as:

$$C = \varepsilon_0 \varepsilon_r \frac{A}{\delta} \tag{5-5}$$

with A as the area of the plates and ε_r as the relative permittivity.

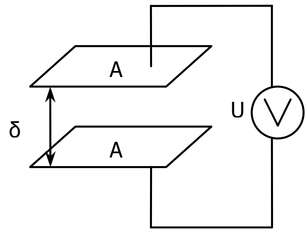


Figure 5-6 Electric Potential in two parallel plates

The energy E associated with this electric potential can be expressed as:

$$E = -\frac{1}{2}CU^2 = -\frac{\varepsilon_0 \varepsilon_r A U^2}{2\delta}\ , \tag{5-6}$$

with U as the applied voltage. A negative sign is attached in the above equation because there is a loss of the potential energy with increases of the applied voltage.

The associated electrostatic force that is normal to the plates in the vertical direction can thus be derived from the potential energy and expressed as:

$$F_E = -\frac{\partial E}{\partial \delta} = -\frac{1}{2}\frac{\varepsilon_0 \varepsilon_r A U^2}{\delta^2}\ . \tag{5-7}$$

Although the above noted equation gives a first order estimation of the grip force, it should be noted that the calculation is simplified, *e.g.* does not take into account the fringe effect. Meanwhile, it is difficult to estimate the force interaction in a more complicated and realistic gripping condition, *e.g.* with multiple objects in the vicinity of a gripping contact. In this case, a finite element model is more flexible and direct in simulating a gripping process in action.

In this research, a finite element model is constructed to examine the grip force. Furthermore, this model is experimentally verified by using a force test bench, which has same geometrical parameters and physical boundary conditions as applied in the finite element model. In the first step, the computer model is tuned and validated according to the experimental results gained from the test bench in a simple working condition, shown in Figure 5-6. In the second step, the computer model is applied in an effort to estimate the grip force in a more realistic condition.

5.7.2 Structure of an electrostatic gripper and force test bench

A gripping and force measurement system has been developed and the structure is shown in Figure 5-7, together with its equivalent circuit. The gripper is constructed as a cylinder with a diameter of 5.7 mm. The material is aluminium. A piece of wire is attached to its top. Different electrical potentials can be applied via this wire. A piece of glass with a thickness of 0.18 mm is used as an isolation layer, which is stuck to the bottom of the gripper with conductive glue. The gripper is attached to a robot. The two entities are electrically isolated from each other. The force measurement part includes a cantilever beam with a well-defined spring constant, and a laser displacement sensor, which measures the deflection of the cantilever. The smallest force increment that can be measured is 8 μN. In the setup, the cantilever, the displacement sensor and the robot are all grounded and isolated from the gripper.

When enough potential difference is added between the gripper and the cantilever, the cantilever can be pulled up. The displacement sensor measures the deflection value, which is converted to force value.

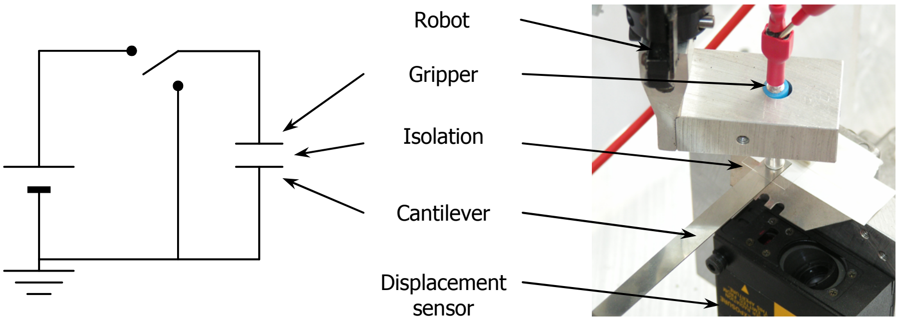


Figure 5-7 The equivalent circuit of the gripping system and the structure of the test bench

5.7.3 Finite element model

Modelling the precise force interaction is difficult and not the ultimate goal of this work. Simulation is used to provide a good understanding of the gripping process and the acting force in the interaction. A wide variety of parameters influence the process in reality, and this can sometimes lead to a considerable difference from the simulation results. For simplification and verification, a model is made in Ansys emulating the measurement setup, which is shown in Figure 5-8.

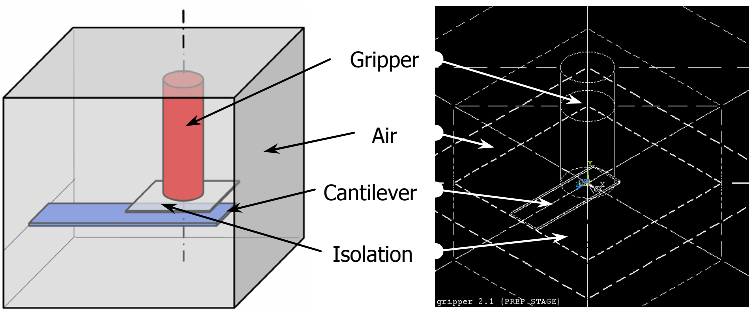


Figure 5-8 The frame structure of the gripping system model

Electrical and geometrical boundary conditions are applied to the model. The cantilever is set to 0 V, and the gripper is assigned a potential value, for instance 800 V. In order to simulate the operation condition, all the areas that surround the gripper and cantilever are defined as infinitive space. After all the boundary conditions are set, the solution can be calculated.

5.7.4 Model validation

To make use of the model, the simulation results of interaction forces are first compared to the measured value on the test bench, shown in Figure 5-7. This model is then applied to study the grip force under different geometries, voltages, and gripping situations.

On the test bench, the force is measured and calculated by the deflection of the cantilever under certain potential differences and a certain distance away from the gripper.

First, it is crucial to know the distance between the gripper and cantilever in this measurement. The gripper is moved away from the cantilever and the displacement is set to zero on the deflection sensor. This will be the point of reference. The gripper is then moved in and brought closer to the cantilever. Meanwhile, 830 V is added to gripper. When the distance between the gripper and cantilever becomes small enough, the cantilever jumps towards the gripper and makes contact with the isolation layer. The position of the gripper compared to the reference point is then known by reading the deflection. The gripper is then switched off and grounded.

Next, a smaller potential is set between the gripper and the cantilever. The cantilever will bend but not touch the gripper. The air gap is known from the difference between the position of the gripper and the reference point. From the displacement of the cantilever, the force is calculated. With the distance of the air gap and the known potential, the force can be calculated and compared with the model.

Using the model, thirty different combinations of distance and potential were modelled. The results are shown in Figure 5-9. A power curve is fitted to the data. The two curves and two equations shown in the graph correspond to 500 V and 830 V. The equation in the bottom left of the graph area corresponds to 500 V, and the one at top right corresponds to 830 V.

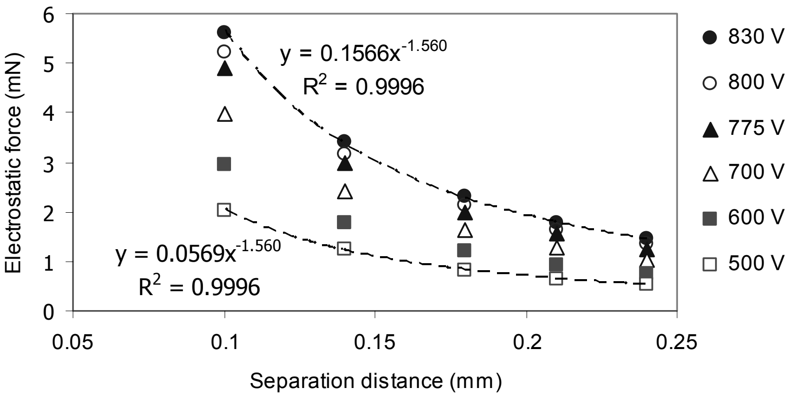


Figure 5-9 Graph of calculated forces

Figure 5-10 shows a diagram of a series of measurements, which were performed under potential differences of 500 V and 700 V. The vertical axis shows the electrostatic force, while the horizontal axis shows the distance between the cantilever and the isolation layer. As shown in the figure, the predicted values correspond well to the measured values and to the values calculated with the analytical model, although the measured electrostatic force is influenced by the humidity of the air and the quality of the bonding with the glue.

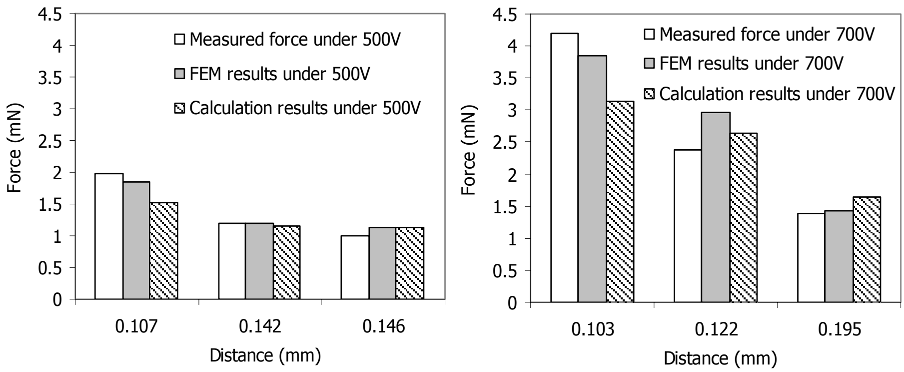


Figure 5-10 Measurements compared to model

5.7.5 Prediction model of the gripping operation

In an actual gripping operation, the gripper may come close to a structure or object when a component is gripped. Due to induction, the gripping contact may be influenced. It is of interest to know whether the grip force is influenced under this circumstance.

The 3D model presented above is modified to investigate the influence on the grip forces if a third object comes close to the gripper while it operates. Figure 5-11 shows the model. A square-shaped, flat object with dimensions of 8x8x0.5 mm^3 is modelled as the target object. The part is aligned under the centre of the gripper. The object inserted into the model to disturb the electric field is a cube with dimensions of 5x5x5 mm^3. The centre of the cube is positioned 10 mm above and 10 mm sideways from the centre of the bottom of the gripper. The boundary condition on the disturbing cube is set to 0 V (grounded). The gripper has a potential of 800 V compared to the part and the object. The air gap between the isolation layer and the part is set at 0.4 mm. This is much larger than what actually occurs. The Y direction points upward in the model.

The change of the potential field can clearly be seen by comparing the two graphs and the influence can be interpreted. The potential field loses its symmetry when the cube is added. However, the change of the overall grip force is very limited (0.7%) in vertical directions. In the horizontal directions, the forces are smaller than a micro-Newton, which are in the same magnitude of the possible errors generated by the modelling process.

The simulation suggests that a grounded object in the vicinity of the gripper does not have a large influence on the gripping contact. The details of the force interaction and value are shown in Figure 5-11.

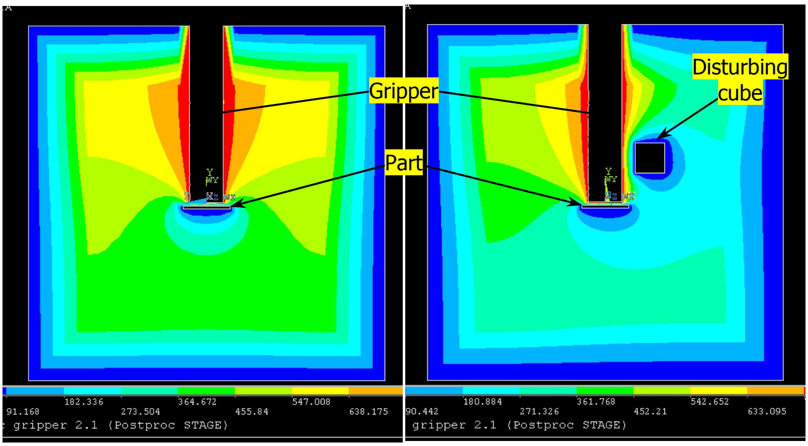


Figure 5-11 Potential field and forces, with and without a grounded object
(Forces without object: Y= 5.86E-04 N, X= 2.68E-07 N, Z= 3.56E-08 N.
Forces with object: Y= 5.82E-04 N, X= -5.31E-07 N, Z= -3.75E-09 N.)

5.7.6 Experiments and observation

Pick-up and placement experiments were conducted to evaluate the actual performance of the gripping system. Parts made from different conductive and non-conductive materials were tested. A test with copper parts is discussed here. The gripper used in this test had a diameter of 400 μm, and was isolated with 100 μm PTFE layer, rather than glass. The target object had measurements of 1500 μm in diameter, and 100 μm in thickness copper disks. Different voltages were set between the gripper and the part. To release the part, the strategy was to reverse charge the gripper. For every test condition, the experiments were repeated for few tens of times. With 300 V added, the probability of pick-up was 90%, and the probability of release was 100%. With 200 V added, the probabilities were 35% and 57%, respectively. With 150 V added, the successful rate was 0. The gripper is also able to pick-up plastic parts. The probabilities of picking up non-conductive or conductive parts are comparable, but releasing a non-conductive part is more difficult.

5.7.7 Brief conclusion of the study on electrostatic gripping

According to the experiments and observations, electrostatic gripping can provide adequate force to pick up small objects. The dimension of the gripper can be designed smaller than the target components. Furthermore, the same gripper can be applied to handle different parts.

In comparison with other means of gripping, the grip force of this method is rather limited. Applying a higher voltage is an option to raise the force, but it may have other limitations. The grip force may decrease, due to the gripped part having contact with conductive objects during the assembly process. If the gripping contact and grip force must be assured while assembly takes place, the applicability of the principle is questionable. In observing the equations of electrostatic force, a thinner isolation layer is beneficial. A gentle contact or a small gap is required in the handling to assure higher force, while keeping the voltage low [Lang06-1].

5.8 Process window for electrostatic gripping

Description and physical model and actuation

A charge difference between two particles causes a force of repulsion or attraction. Electrostatic gripping utilizes this force to operate target parts.

Electrostatic force scales with the second power of characteristic length. Hence, electrostatic force becomes more dominant than gravitational force in the micro-domain. Therefore, it can be stated that it can be positively used as a grip force.

Two methods are used to implement this principle in a gripping operation. One is to charge a gripping unit and the target object with an electric circuit. In this way, the gripper tip and part are directly connected with the power source. According to the number of electrodes contained in a gripper, there are monopolar grippers (which only contain an anode or a cathode), and bipolar grippers (which contain both anode and cathode). In the second method, the handling can also be performed under a scanning electron microscope. By this means, the electrostatic field is generated by the microscope.

Configuration of grip

The grip force depends upon the contact area between the gripper and part, permittivity of the isolation material and its thickness, and the applied voltage difference. The dependency of the grip force can be described as:

$$F_{grip} = f(A, \varepsilon_r, \delta, U) \tag{5-8}$$

The typical value of the specific grip force is in the range of mN/mm^2, under a few hundreds of Volt potential difference. By accurately controlling the voltage difference, the grip force can be fine-tuned.

The grip principle requires one contact surface, preferably the top surface of the target part for the gripping operation. The surface profile of the object must match the profile of the gripper. Alternatively, a smooth and flat grip surface is preferred. A rougher surface or mismatch means a longer distance between the gripper and part, which diminishes the grip force dramatically.

Grip stiffness depends upon the friction and is limited. Grip force may decrease during the assembly process due to electrical-discharge, *e.g.* having contact with conductive objects. Grip force is retainable only along the grip surface against small shifts of the gripped object.

Accuracy performance

In principle, the accuracy performance can be relatively good. The accuracy is highly dependent upon gripper design. The accuracy specifically depends upon how well the pattern of the electrodes matches the geometry of the part.

Damage causes

Residual charges may remain on parts after being handled. Thus, charge sensitive components, (*e.g.* IC chips), cannot be gripped with this principle.

Flexibility

Geometry related: The principle fits for most geometries. Parts with dimensions from a few micrometres to millimetres can be handled. There are more advantages in handling small dimensional parts, as has been illustrated in scaling laws. For larger parts in the millimetre range, the principle works better in handling thin, flat shaped objects. A single gripper can be applied to different types of parts in large diversity. However, the gripping accuracy must be considered because the constraints are limited in the direction along the grip surface.

Material and function related: Both conductive and non-conductive materials can be handled. It is not suitable for electrically and magnetically sensitive materials and IC chips, which can possibly be damaged by the electrostatic field. It is possible to set up the gripping contact on functional or scratch-sensitive surfaces, given that the impact made by the gripper can be minimized by a fine adjustment of the grip force.

Process related: The grip force is generated by electric field interaction, which allows building grippers to have smaller footprints than target parts. Gripping can proceed in a limited work space. The grip force is limited, and may decrease when contacting conductive objects during the assembly process.

Cycle time

The cycle time is very short. The system requires a specific time to accumulate charges to build up the force. Assuming that the gripping system has an equivalent circuit as a RC circuit, with R as the resistance and C as capacitance, in order to generate 95% of the maximum grip force, a gripping time equal to $3RC$ is needed. In practice, the typical grip cycle time is in the milliseconds range.

Typical dimensions of operated objects and applications

Metallic balls in the micro-meter range can be handled, while flat parts in the millimetre range can be handled.

5.9 Process window for capillary gripping

Description and physical model and actuation

Small objects can stick to a handling tool with only a small droplet of liquid between them. The grippers based on this principle handle parts with the force caused by the capillary effect. The force arises over a liquid bridge between two solid objects. The capillary force is the sum of the so-called tension force, F_T, and Laplace force, F_L. As stated in scaling laws, the force scales with the first power of characteristic length, which makes it more appropriate in handling small dimensional parts.

As found in literature studies, diverse liquids, such as water, ethanol, silicone oil, *etc.*, are used as the gripping intermediates.

Configuration of grip

The grip force depends upon the surface tension, the separation distance between the gripper and the part, the material combination of the liquid, gripper and component, the geometry of the gripper, and the volume of liquid (*V*) that forms the liquid bridge. The dependency of the grip force can be described as:

$$F_{grip} = f(\gamma, \delta, V, \theta) \tag{5-9}$$

The typical value of the specific grip force is in the range of a few milli-Newtons, with 1 μL water applied as the gripping intermediate.

The principle requires a minimum of one contact surface for the gripping operation, which should be open for the gripper's approach from above. Grip force cannot sufficiently be built on absorbent, hydrophobic or oleophobic surfaces.

Grip stiffness is very low in all directions, and dependent upon the viscosity of the intermediate. The gripped part can be seen as floating under the gripper tip. The grip force is retainable in all directions against small shifts of the gripped object.

Accuracy performance

The principle offers good accuracy performance in handling geometrically symmetrical parts. Due to the surface tension force, parts tend to orientate and couple with the shape of the gripping contact area. Positioning accuracy further depends upon the geometrical accuracy of the parts and the force distribution in release, *e.g.* acceleration.

Damage causes

There will be a small amount of liquid residue on the part surface after gripping processes. A surface contamination, *i.e.* an imprint, may be left after the handling, as dependent upon the impurity of the liquid and the cleanliness of the grip surfaces.

Flexibility

Geometry related: The principle applies to handling parts wherein the top surfaces have flat shaped or sphere shaped profiles. Parts with dimensions of a few tens of micrometres to millimetres can be handled. It is more advantageous in handling small dimensional parts, as has been illustrated with the scaling laws. For relatively large parts, (*i.e.* parts in the millimetre range), the principle works better in handling thin, flat shaped objects because of its larger contact area over less mass. A single gripper can be applied to different types of parts in a small range. The principle is not suitable for gripping parts with open structures or unsymmetrical geometries.

Material and function related: With some limitations, most engineering materials, can be handled. It is possible to set up the gripping contact on scratch-sensitive surfaces. The liquid gripping intermediate prevents the gripper from creating a mechanical impact on the target part. With careful selection of the intermediate liquid, optical components can thus be handled with their optical surfaces as the grip surface. Absorbent surfaces or structures of the gripping contact may cause the gripping operation to fail. Parts made from hydrophobic or oleophobic material cannot be operated.

Process related: The grip force works over a liquid bridge with the gripper and the part, which allows building grippers to have smaller footprints than target parts. Gripping can proceed in a limited work space. Self-centring effects help to increase the positioning accuracy. However, the grip force and grip stiffness are limited. The part position can be changed subject to the imposed force during the assembly process.

Cycle time

The cycle time is short. It is mainly dependant upon how quickly the liquid bridge between the gripper and part can be formed. The process normally takes place in a few micro-seconds to a few hundred micro-seconds, subject to different viscosities. Release time depends upon the different strategies, and is in the order of milliseconds. The total grip cycle time is typically measured in milliseconds, comparable with that of electrostatic gripping.

Typical dimensions of operated objects and applications

Small dimensional parts with top surfaces in the range of a few hundred micrometres to millimetres are handled successfully. These include optical lenses, IC chips, and spheres.

5.10 Process window for liquid solidification gripping

The data presented in this section is based upon both a literature study and research results stated in the Part II of this thesis.

Description and physical model and actuation

The basis of the principle is that the adhesion force of the intermediate is much greater in its solid phase than in its liquid phase. A small amount of liquid is used as the gripping intermediate, which is then solidified between the gripper and the part. The adhesive property of the gripping intermediate in its solid phase produces the required force, and the gripping is thus established. To release the part, the frozen material is broken, and/or melted and evaporated.

Configuration of grip

Grip force depends on (1) the material of the part, gripper tip and liquid; (2) surface roughness; and (3) the gripping temperature.

The principle produces a high specific grip force of up to 1 N/mm^2, as stated in literature [Patent EP 1319613]. One contact point is sufficient for the handling operation. It is possible to set the grip surface at any angle in case accessible by the gripper. The grip surface cannot be hydrophobic.

Grip stiffness is high in all directions, since the gripper and the target part are bound with a solid state intermediate. The stiffness is dependent upon the gripping temperature and the strength of the intermediate. Grip force is not retainable in any direction. Any shifts of the gripped object cause a break of the gripping connection, and thus the end of the grip force.

Accuracy performance

Melting during release may lead to unwanted motion, if the part is insufficiently supported. The influencing factors are force change and position change, due to the phase transformation.

Damage causes

There will be a small amount of liquid residue on the part surface, and this may leave an imprint after the handling operation. The visibility of this surface contamination is dependent upon the impurity of the liquid and the cleanliness of the grip surfaces. The gripping process introduces a thermal cycle, which may cause a thermal interference to sensitive parts or operation environments.

Flexibility

Geometry related: The principle fits most geometries, including large unsymmetrical shapes. Parts with dimensions from sub-millimetres to millimetres can be handled. A single gripper can be applied to different types of parts in large diversities.

Material and function related: Most engineering materials, except hydrophobic, can be handled. It is possible to set up the gripping contact on scratch-sensitive surfaces in most cases. The gripping contact begins and ends when the intermediate is in its liquid phase, which prevents creating mechanical impacts on the target part.

Process related: Sufficient grip force can be built up via a much smaller contact area than the footprint of the part, which allows the gripping to proceed in a limited working space. The principle may cause thermal interference or local condensation in the handling environment or to the target part.

Cycle time

The cycle time is rather lengthy, due to the freezing/melting process. The cycle time is dependent upon the thermal properties of the gripping intermediate and target parts. Fundamentally, the gripping process is an energy exchange process. Thus, the grip cycle time is also dependent upon the execution strategy and the gripper design. Grip cycle times of 4 to 9 seconds have been found in literature studies. A grip cycle time of a minimum of 0.1 s is achieved in this research.

Typical dimensions of operated objects and applications

Mechanical parts, made from diverse engineering materials, with dimensions in the millimetre range can be handled.

5.11 Summary

The framework defined in this chapter structuralizes the knowledge of the micro-gripping technology, and establishes a systematic understanding of both the theoretical and application issues of all available grip principles. The framework provides a method for the comparison and selection of proper methods for specific gripping applications. It serves as a guideline for the implementation of micro-gripping in assembly processes. Meanwhile the framework is the foundation and input of the process planning for micro-assembly [Fleischer06].

It can be concluded from the framework that electrostatic gripping and liquid solidification gripping have less research activities than other principles, but still have fairly high potentials for applications. However, the understanding of these principles is rather limited. Modelling, together with experimental study of electrostatic gripping, was performed in this research and is reported in the previous section. The results are used in the compilation of the framework.

The liquid solidification grip principle shows high application potential because of its relatively high specific grip force and grip stiffness, and good gripping flexibility with respect to part materials and part geometries. However, the understanding level of the principle is inconclusive. This principle is chosen for further research in this project, in an attempt to garner a better understanding of the principles, and to apply the principles to industrial applications.

The next part of the thesis is dedicated to discussing the study and technology development of liquid solidification gripping.

Part II. Development of liquid solidification gripping

On the basis of the industrial study stated in Chapter 1, it is clear that there is a need for alternative gripping methods,, other than friction or vacuum gripping. The principle in demand, according to the study, should have better flexibility, a higher grip force and better grip stiffness. The framework of the micro-grip principle defined in Chapter 5 has shown that liquid solidification gripping can offer a promising solution, with a high potential grip force and good flexibility. However, more research into the performance specifications of the grip principle is required, including grip force and its determining parameters, and process related issues. Meanwhile, for the interest of application, the grip cycle time should be much less than the 9 seconds as stated in literature. In this research, steps are taken to gain more knowledge into the principle of liquid solidification gripping, and to develop gripping systems with a shorter gripping cycle (approximately 1 second). A fully functional gripping system is developed as an approach to study the application related issues.

This Part is dedicated to the study of liquid solidification gripping. The general approach taken in this study can be stated as such: gripping concept investigation, prototype development, system and process odelling, and performance study by experiments. This Part consists of following contents:

The possible gripping concepts and gripping intermediates related to implementation technologies are addressed in Chapter 6. The chapter presents in detail the study and experimental investigation of novel concepts for micro-gripping applications. Water is chosen as the gripping intermediate for further development.

In Chapter 7, the development of a series of gripper prototypes is discussed. The prototypes served for different goals throughout the research path, from identifying the physical parameters and application issues, to reducing the grip cycle time, to developing a fully functional gripping system towards industrial application.

The gripping process is thermally modelled with finite elements. The models are addressed in Chapter 8.

Chapter 9 focuses on the experiments and tests of application issues with respect to the grip principle. Grip cycle time and grip force are the major parameters to be addressed.

6 The concepts of liquid solidification gripping

Liquid solidification gripping, with water as the gripping intermediate, has exhibited excellent application potential, showing a relatively high specific grip force and flexible applications. The aim of this chapter is to research alternative physical and/or chemical processes and gripping intermediates, in an attempt to gain an overview of the possibilities of the grip principle. In the following sections, the study of the principle is broadened by abstracting the identical process of the grip principle, whereby an intermediate is applied between the gripper and target part in the gripping operation, while the intermediate alternates between its solid and liquid phase for the pick-up and release processes.

Firstly, the experimental setup and devices used in the research are stated. Following that, the investigations of four diverse materials used as potential gripping intermediates are addressed in the individual sections.

6.1 Experimental and test equipment

The development of the gripping concept is supported by experiments and tests. The performance of the gripping concept and detailed gripping process discussed in the following chapters are investigated with a set of measuring and observational equipment. The main test setups and equipments are described in this section.

Force test bench

Grip force is one of the most important parameters of a grip principle. In order to test the maximum grip force at the moment the gripping connection breaks, a measurement system is needed with sufficient measuring range, accuracy, and rapid response. A force test bench is designed and built for this purpose. The test bench is designed to have measurements in the range of a few milli-Newtons to Newtons. The measuring accuracy is defined to be in the micro-Newton level. The maximum sampling frequency of the system is 50 KHz.

Small force measurements can be accomplished by measuring the material deformation. On the basis of this principle, a cantilever system is chosen, which measures the deflection of a well calibrated beam when the force is applied. The deflection is measured by a laser displacement sensor. One advantage of this method is that it can measure a force with sufficient accuracy. Meanwhile, by changing the cantilever in use, the measuring range can easily be adjusted. The cantilever is designed to clamp at both ends. In the configuration, the tilting angle of the beam is eliminated in the measurement. From the experiment, it is known that the tilting of the cantilever results in bending inside of the gripping intermediate, which heavily influences the testing result.

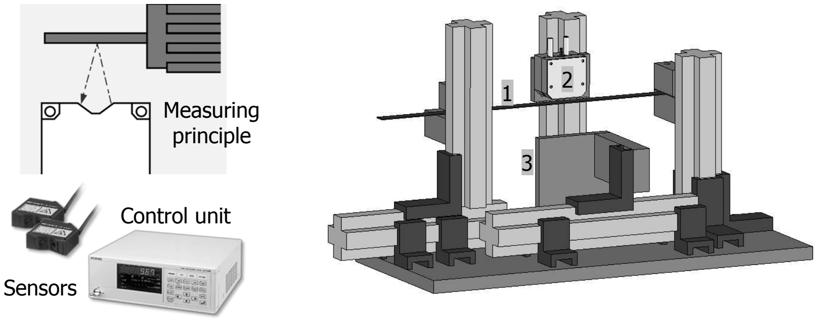


Figure 6-1 Force measuring principle and setup configuration

As partly shown in Figure 6-1, the test bench includes (1) a deflection cantilever that supports and holds the gripping sample, the cantilever is fixed with two cantilever holders that clamp the beam at both ends, (2) a gripper holder with sliding mechanism, which positions a gripper at the right spot on the cantilever, and (3) a laser displacement sensor Keyence LC-2400W (only the holder shown in the figure), which measures the deflection of the cantilever at the middle. Other systems not shown in the figure include control systems, a PC for data analysis, and a Sankyo SCARA robot which handles the gripper head.

The relation of the force that is applied at the middle point of the cantilever and the measured deflection at the same point is given by:

$$F = \frac{KEI\delta}{L^3}, \tag{6-1}$$

with K as the constant, F as the force, E as Young's Modulus, I as moment of inertia, δ as the deflection, and L as the length of the cantilever. In applications, system calibration is always performed before the taking of any measurements. In this process a series of forces with known values that covers the measuring range are applied at the gripping point. The deflection is logged to produce the calibration curve. In Figure 6-2, a calibration curve is shown with the force-deflection function that was produced from the calibration.

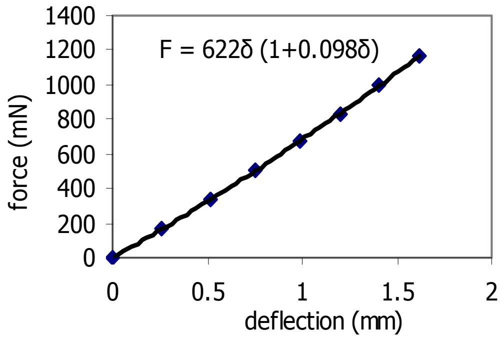


Figure 6-2 Calibration curve and force-deflection function [Warner07]

Microscope

For geometrical measurement and microscopic observation of the detailed phase of a gripping process, a multifunctional digital microscope VHX-100 from Keyence is used. The system allows observation and geometrical measurements under 20X to 3000X. In combination with a long focus distance lens, it is possible to examine the gripping process at the gripper to object contact point. The microscope is also used in measuring the gripping sample and inspecting the surface contaminations on the object. The gripping accuracy is recorded and measured by the same system.

Surface roughness

The surface roughness of the gripping contact influences the maximum grip force. In order to gain a more quantified understanding of this influencing parameter, the surface roughness measurements of the small gripping samples (in the range of a few millimetres) are carried out by a tactile roughness recording device, a Talysurf Series 2 from Taylor Hobson.

6.2 Gripping intermediates selection

Liquid solidification gripping utilizes the adhesion force variation and physical property change of gripping intermediates to perform the gripping and releasing operations. Under the scope of this principle, many physical and chemical processes can be applied. A gripping technology consists of the combination of an intermediate and a particular phase changing process. For instance, water can be used as an intermediate, with the phase changing being accomplished with temperature changes. The attaching (picking up) process is achieved by solidifying water between the gripper tip and the part, while detaching (releasing) the part is achieved by melting the water [Lang07]. The physical and chemical properties of the intermediate and the corresponding process influence the scale of the grip force, the cycle time and the application flexibility in general. It eventually determines the process window of the gripping process.

A broad study of literature, applications, feasibility, and experiments conducted in this research helped to gain a detailed view of the different parameters that influence the applicability. The general demands of the intermediate material can be extracted as follows:

- Reasonably high adhesion force → more applications;
- Low power consumption on liquid-solidification process → low cycle time;
- Leaves no/less stains on object → more applications; and
- Non-poisonous and non-corrosive → does not harm objects or the environment.

To alternate a material between its liquid and solid state (or solid-like state) or gaseous state can be achieved through different physical or chemical processes. In Figure 6-3, an illustration is given of the links between potential physical or chemical phenomena, energy exchange forms, enabling processes, and gripping intermediate materials.

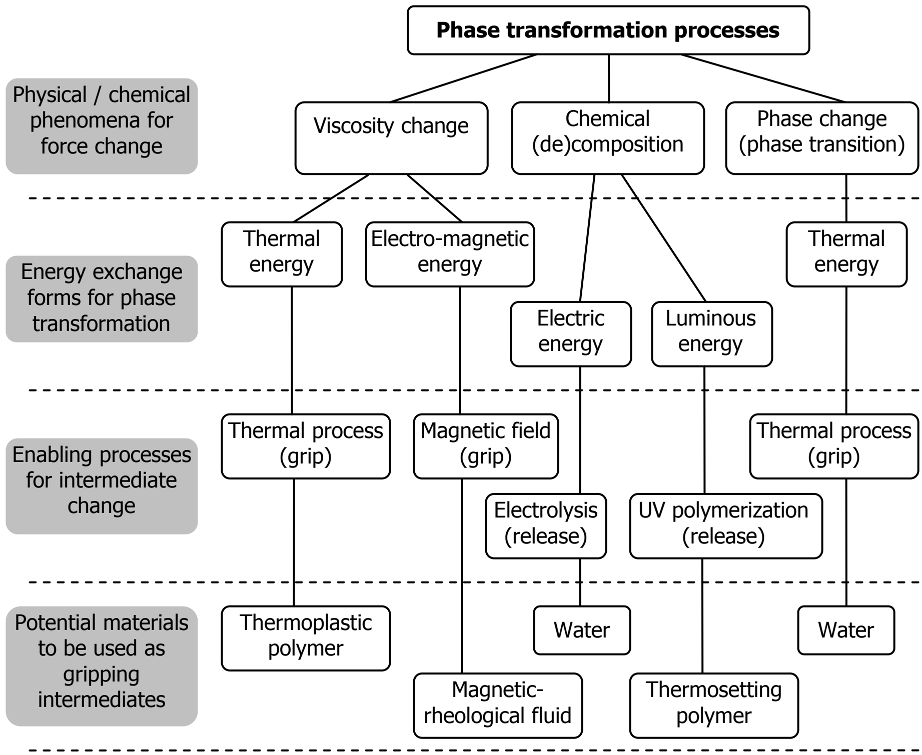


Figure 6-3 Overview of intermediates and corresponding technologies

In Figure 6-3, the “liquid-solidification process” is replaced with the more general term of “Phase transformation processes”, which covers at least three different physical or chemical phenomena, including viscosity change, chemical property change or phase change. In order to produce these phenomena, diverse processes can be employed. For instance, a material can be melted or solidified by changing its temperature, or certain UV sensitive fluidic polymers can be hardened due to a chemical reaction by exposing it to a UV light. Other polymers, such as paraffin, become soft and even fluidic by raising the temperature, while the chemical properties remain unchanged. The diverse physical and/or chemical processes and potential gripping intermediate materials are investigated and described in more detail in the following sections.

6.3 Thermoplastic polymer as a gripping intermediate

A thermoplastic is a polymer that has a reversible phase change. Essentially, the same processing technology for water can be used with a thermoplastic. However, the power consumption for hardening a thermoplastic material can be lower. Other advantages are that it is non-poisonous, non-corrosive and has a low purchase cost, which makes the intermediate of serious interest for this investigation. The material has the disadvantage of leaving residue on the object after the gripping and releasing processes.

6.3.1 Implementation method

Application of a temperature change is used to transform the intermediate between solid-like and liquid phases. By heating and cooling, the characteristic of the polymer is changed and it can be done repeatedly without chemical change. In other words, the liquid-solidification process is achieved with a reversible physical process. The grip force is established by means of changing the intermediate from a liquid to a solid phase. The releasing process is accomplished by changing the gripping intermediate from a solid to a liquid phase.

In order to benefit from the material property, the type of polymers that have their solidification or hardening temperatures above ambience temperature are chosen as the gripping intermediates. This is done so that the heat loss in the system and to the environment can be minimized. Meanwhile, by selecting the materials with a lower specific heat, the power consumption in the process can be reduced. Accordingly, the grip cycle time is expected to be shorter.

6.3.2 Performance tests

A commercially available polymer (FlexWax ®) is used for the preliminary tests. The polymer is solid-like at room temperature. When heated above 52 ^{o}C, it becomes a liquid. A small amount of the polymer, approximately 5 μl, is applied on the top of a target object. The polymer is preheated to its liquid phase, while the gripper is cooled to 15 ^{o}C.

This should be the lower limit of the application temperature for the intermediate. The initiative of using this type of material is to minimize the cooling procedure in the gripping operation. Meanwhile, the lower temperature results in a condensation layer around the gripper tip, which considerably reduces the possible grip forces. A reliable gripping time of 3 seconds is achieved in the experiments. It should be noted that one of the expected advantages of using thermoplastics is that it is not necessary to cool the gripping system. This, in turn, enables the system to be smaller and simpler. However, as exhibited by the test results, a longer attachment time can be a drawback.

The grip force test with the polymer is carried out with the force test bench. Following calibration, the component is connected to the top of the deflection beam, and a small amount of the intermediate is put on the top surface of the object and attached to the gripper tip. The gripper is moved by the handling robot and lifts the component.

The highest grip force of 58 mN/mm^2 is achieved at room temperature, when using large amounts of the polymer, over a large grip area of 12 mm^2. In this case, the gripper tip is already partly embedded in the bulk of the polymer. When reducing the amount of the polymer and grip area, the value of the grip force per unit area did not reduce proportionally and did not result in the same adhesion value. From [Thompson01], combined with the results of the experiments, it can be concluded that the polymer shows higher cohesive forces than adhesive forces.

The results indicate that imprint is a major concern when using a polymer as a gripping intermediate. The polymer remains in a solid state and does not evaporate at room temperature. After the part is released, the intermediate leaves a residue on the target object. Meanwhile, the contact angle of the polymer to the target object is very small, which means that the polymer tends to flow to the gripper surface and onto the part surface. Consequently, it is difficult to form a sufficient gripping interface. A larger amount of the polymer must be applied to establish the connection between the gripper and the object. Adding these two facts together, a considerable amount of residue is left after each gripping operation. The comparison between water and polymer intermediates is shown in Figure 6-4.

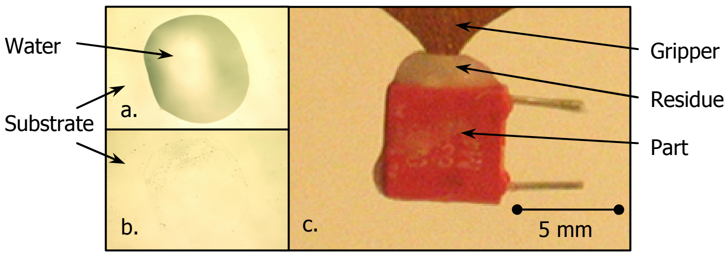


Figure 6-4 The comparison between water and polymer
a) purified water droplet (0.1 µl) on a glass surface;
b) no visible imprint after water evaporated; and
c) residue of a polymer in an extreme example.

6.4 Magnetic-rheological fluid as a gripping intermediate

A magnetic-rheological fluid is a colloidal material with a stable suspension of solid magnetic particles in a carrier fluid. The particles consist of a magnetic solid, with sizes of up to a few micrometres in diameter. Examples of magnetic materials that are being used are cobalt, iron or more frequently, magnetite (Fe_3O_4) [Brabander05]. Normally, the magnetic ferrofluids contain approximately 20% to 40% volumetric concentration of these magnetic particles. Many different fluids can be used as a carrier fluid, including heptane, kerosene, synthetic esters, synthetic, hydrocarbons, *etc.* Aggregation of the magnetic particles is prevented by a surfactant coated on the particles, which prohibits the particles from getting too close to each other.

In 2002, the inventor M. Haag developed a system for holding small parts [Patent DE 10209783]. Specifically, it was a handling box filled with magnetic-rheological fluid. By applying an electromagnetic field, the viscosity of the fluid significantly increased. When sufficient field strength was applied, the fluid eventually solidified. This can be used to hold a component in a small bath of the fluid. With this method, a part can be moved or assembled. By changing the field again, the viscosity of the fluid drops, allowing the part to be released.

The characteristics of this fluid have been known since 1960, but it has not yet been applied in the field of micro-gripping. The type of material exhibits the potential for it to be used as a gripping intermediate. However, it must be noted that the liquid is usually highly toxic, corrosive and dangerous to humans. With respect to the limitations of the current research, the potential of this intermediate is not further investigated.

6.5 Thermosetting polymer as gripping intermediate

Thermosetting polymers (thermosets) are a class of materials with a relatively low viscosity at room temperature, which are curable under certain amounts and sorts of energy inputs. Depending on the composition, the polymer has different viscosities. The curing of a liquid polymer is achieved through the addition of various energies. Typically, these are heat, generally above 200 ^{o}C, a chemical reaction, and radiation (*e.g.* UV light). The polymers are contrasted with thermoplastic polymers, since thermosets do not have a reversible phase change process. After the polymerization process, the solidified thermosetting plastic cannot be melted or remolded again.

These types of polymers have been used for fixing and joining parts at certain locations [Shimada00]. The usage of thermosets as gripping intermediates is a novel approach. The explorative study is detailed in the following sections.

6.5.1 Implementation method

UV light curable polymers are especially interesting because of their low reaction temperature and high curing speed. UV light initiates free-radical polymerization with very low activation energy. This allows high polymerization rates at room temperature, due to the fact that the rates are not temperature dependent in the early stages. With suitable light sources (wavelengths of 254 nm to 450 nm [Kim04]), the liquid resin is transformed into a solid polymer in a very short time, within the range of a few milli-seconds [Scherzer99]. In combining the UV laser device and proper optical fibre, it is possible to achieve a very compact gripping device.

The method ensures that the object is gripped and held using the surface tension forces of the thermosetting polymer, and releases the object by using the UV polymerization process that decreases the adhesion of the polymer. Normally, after curing process the adhesive/cohesive forces of the polymer will rise, which means it holds the object more firmly. However, the polymer can be chemically changed so that the polymer layer mechanically breaks in the UV polymerization process, resulting in losing its adhesive/cohesive forces after polymerization. In this manner, it releases the component. The compositions of the polymer and detailed implementation strategies are further described in the performance test section.

6.5.2 Explorative experiments and performance tests

The idea of using thermosetting polymers as gripping intermediates is rather innovative. A series of experiments has been carried out in an attempt to validate the concept. It should be noted that the experiments are explorative and not all aspects are covered. Furthermore, development of a satisfactory polymer formulation could be a field of research in itself.

As stated above, attachment of the object is achieved by using the surface tension forces of the thermosetting polymer and releasing the object after the UV polymerization process. Several investigations (*e.g.* [Lambert03-2]) prove that the principle of surface tension is strong enough to lift micro-parts. An investigation of the adhesion force of the thermosetting polymer is undertaken in the above mentioned measurement setup. Following calibration, the part is prepared for measurement with a polymer intermediate layer applied to the top of the object. The maximum grip force of 14.6 mN/mm^2 is achieved at room temperature, when using the polymer with the highest viscosity (among all applicable polymers that were developed in this research) before polymerization. The mixture MMA consists of 500 mg PMMA (Polymethylmethacrylate), 120 mg IRGC907, 2 g MMA, and 1 g TMPTA (Polytrimethylolpropane triacrylate).

Releasing is achieved by curing the thermoset into a solid state with UV light. In order to achieve this, the polymer must lose its adhesive/cohesive forces in the curing process. Specific formulations must be developed to adjust the mechanical properties of the polymer.

UV-curable formulations are usually composed of three basic components. These are a photo initiator, functionalized oligomer, and a mono- or multi-functional monomer [Decker02]. In this general formulation:

- A photo initiator effectively absorbs the incident light and readily generates reactive radicals or ions;
- A functionalized oligomer, upon polymerization, will constitute the backbone of the three-dimensional polymer network to be formed; and
- Mono- or multi-functional monomers act as a reactive diluent to adjust the viscosity, which in turn incorporate into the polymer network.

The mechanical properties of the cured polymer can be influenced by the type and concentration of the photo initiator, reactive diluent, and solvent.

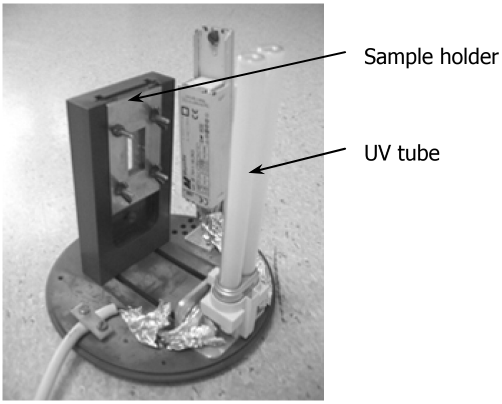


Figure 6-5 Curing setup with sample holder and UV light

A curing setup is used in order to investigate the various influences of the formulations in relation to the mechanical properties of the cured polymer. The setup is shown in Figure 6-5. A 25 Watt UV light source with a wavelength of 254 nm is used in the experiments. The polymerization process takes approximately 2 minutes, due to the low power light source. It should be noted that 2 minutes is too lengthy a time for a release method. However, the experimental setup is meant solely for feasibility study purposes. The release time (polymerization time) can be reduced in theory to milliseconds by using a stronger light source, (*e.g.* a UV laser source with optical fibre). Having said that, there are practical issues to be considered and solved in further development, which are not addressed in this research.

Influence by photoinitiator: Various experiments [Kim04] indicate the change of the mechanical properties of the acrylate films by introducing different amounts of photo initiators into the mixture. If the level of the photo initiator is in excess, problems can arise, such as insufficient dissolving or mixing within the resin system. Even in a system wherein a large amount of a photo initiator is compatible, most of the photo initiator will remain chemically unbounded in the final cured product, causing deteriorative effects on the properties of the cured materials.

To develop this low tensile strength film, 120 mg, 3 times more than the normal amount of photo initiator (IRGC907), is put in the acrylate resin (3.5 g *e.g.* TEEGDMA and PMMA). This definitely causes deteriorative effects in the unsolved photo initiator and causes low tensile strength. The result is shown in Figure 6-6, with a possible application concept. The polymer becomes brittle and has very little adhesion force to the glass surface.

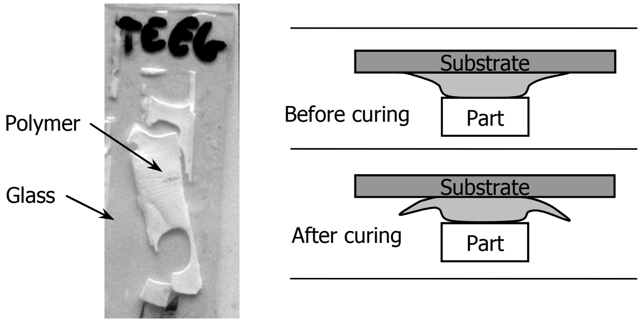


Figure 6-6 (Left) result of adhesion force change after UV curing, shown as white polymer sample on top of a pieces of glass substrate, and (right) a possible application concept

Influence by solvent: A more obvious effect is apparent when more solvent is added to the mixture in order to solve the reactive diluent and the photo initiators. Following the first trial, all of the resin systems came off very easily. This can be explained by the fact that when the sample is opened, one of the plates is peeled off, which is mostly clean. The film remains attached to the plate on the other side. As soon as the film contacts the air, the residue of the solvent, which remains in the mixture, diffuses suddenly out of the polymers and into the air. The side that is exposed to the air dries faster than the other layer attached to the glass. A variation in drying speed results in large cracks and the layer begins to crumble. In approximately 5 seconds, the entire layer dries, becomes completely non-sticky, and falls off the plate.

It should be noted that the solvent makes the mixture thinner, which reduces the contact angle of the polymer and the glass. The surface tension force drops simultaneously. Further experiments are conducted in order to optimize the viscosity of the mixture, while maintaining good releasing properties. The best result, after a minimum curing time of 4 minutes, is shown in Figure 6-7, with a possible application concept. The layer only has a few spots still attached to the glass. The mechanical strength of the polymer is significantly reduced, as it starts falling apart into small dust particles.

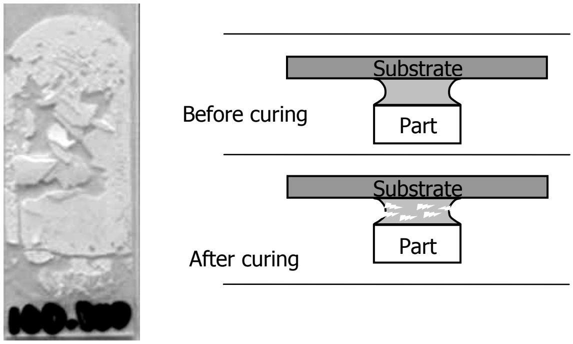


Figure 6-7 (Left) result of adhesion force change after UV curing, shown as white polymer sample on top of a pieces of glass substrate, and (right) possible application concept

The experiments prove that it is entirely possible to develop a complete working concept for a micro-gripping operation; for instance a sticky tape that is non-sticky when it is cured under a UV light for a few milliseconds. The principle has the potential advantages of a very short grip cycle time, a relatively large specific grip force and good application flexibility. However, the study of this gripping concept is extremely dependant upon choosing the proper polymers as the gripping intermediate. Substantial knowledge from a chemical perspective is required to develop and optimize thermosetting polymer formulations.

6.6 Water as a gripping intermediate

Water is an ordinary material, which freezes at 0 ^{o}C at standard atmospheric pressure. The general adhesion force between water and solid materials is much smaller than that between ice and solid materials. This makes water an interesting substance to be used as a gripping intermediate. Water is a non-poisonous and low cost liquid. It is non-corrosive to most of the engineering materials in a short interaction time. In the fluid phase, it has a very low viscosity, which ensures an easy dispensing method and easy release after assembly. When using purified water, it does not leave obvious stains on the component. The disadvantage of using water is the power consumption, which requires rather high energy levels in its phase changing process. This is the reason for the long cycle time observed in earlier investigations [Kochan97], [Kurniawan04].

6.6.1 Implementation method

Temperature changing is a method to transform the intermediate between solid and liquid states (between water and ice). The gripping contact is set up by freezing water between a gripper and the object. A water film can easily be put onto the target object and an internal thermal actuator can cool down both the part and the water layer until the water becomes ice. When the liquid becomes a solid, it has high grip forces, up to

1 N/mm² [Kochan97]. Releasing the object can be achieved by heating the ice film. The ice becomes water and loses its grip force.

6.6.2 Performance tests

The same testing setup used for thermoplastic is adopted for the performance tests of water. The test focuses on experimenting with the freezing time of water. A volume of 1-5 μl of water at room temperature is applied on top of a target object. The gripper head is pre-cooled down to -10 °C, -15 °C, -20 °C before touching the target object. The time for attaching an object is in the range of a few seconds to a single second. It has been recorded that the lower the temperature the gripper is pre-cooled, the shorter the pick-up time. The experimental results show that the cooling time for water is shorter than that for thermoplastic polymers.

Water also shows interesting results in other experiments when used as a gripping intermediate. In a grip force test, at a temperature of -20 °C, a force value of approximately 1 N/mm² was measured (discussed further in Chapter 9), which is comparable to the known results stated in [Kochan97]. Of all tested materials, including glass, aluminium, and plastic, water remains on the object surface as a drop. Meanwhile, it forms a good and sufficient contact with the object. The imprint that is left after the gripping and releasing cycle is not obvious. When tap water is applied, the stain is visible for bare eye observation. In the case where demineralised water is used, the stain is only partially visible under microscopic observation. The issue of imprint is further discussed in Section 7.1.

6.7 Novel releasing methods for water as gripping intermediate by electrolysis

Resolving the gripping contact by heating up the interface is discussed in Section 6.6. However, at the moment the ice layer is heated, the releasing actuator unavoidably heats the gripper tip, which has a negative influence on the grip cycle time and power consumption.

A releasing strategy that can break the gripping contact with a minimum or without thermal effect and without mechanical impact would be worthwhile investigating. Electrolysis can be one of the preferred alternatives for a releasing principle. As an electrochemical process, electrolysis does not heat up the system. Instead, the process decomposes the ice into oxygen and hydrogen gases by use of the electrodes. The contact can be broken with the accumulation of the gas in the griping interface.

The application of electrolysis is novel to the micro-handling field. The application principle and experimental investigation are described below.

6.7.1 Application principle

A special formation of water, called the quasi-liquid layer, exists in the contact interface between ice and a solid object. The layer has different physical properties than solid ice, but resembles the characteristics of water. The existence of the quasi-liquid layer was proposed by Faraday in 1859 [Archer98], at temperatures as low as−30 °C. According to recent research, the layer also exists at temperatures of −157 °C, [Web].

In previous decades, experiments have shown that the layer appeared to be highly electrically conductive. Near the surface layer, the conductivity is six orders of magnitude greater than the specific conductivity of solid ice, [Ryzhkin01]. This property naturally builds the condition for electrolysis. In [Web], it is proposed that frozen water acts as a 'protonic' semiconductor, and that the current is carried by hydrogen ions (proton), which jump between water molecules in the ice lattice. In addition to the transportational charge through the ice, the movement of protons can cause the water molecules to rotate within the lattice. This means that the flow of the charge can alter the ice's mechanical properties. It is discovered that applying a small potential difference to ice could change the adhesion dramatically.

With a DC voltage applied to the contact layer (quasi-liquid layer), the electrolysis effect generates oxygen gas on the anode and hydrogen gas on the cathode. The gas accumulates in the form of interfacial bubbles that interrupt the integrity of the interface around the electrodes. By evenly distributing the anodes and cathodes to the entire gripping contact area, an effective layer is built for the releasing action. The design of a releasing element on the basis of electrolysis is illustrated in Figure 6-8.

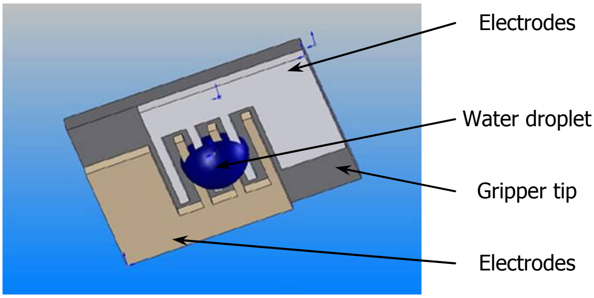


Figure 6-8 Design of a releasing element on the basis of electrolysis [Blom05]

The most important advantage of this releasing principle is that the method applies minimum thermal heating energy to the interfacial layer to melt the top layer of the ice. In comparison to the releasing methods by heating to remove ice, electrolysis does not negatively influence the grip cycle time.

6.7.2 Performance test

Components equipped with anodes and cathodes that can generate the electrolysis effect are developed for testing. The design, as shown in Figure 6-9, is implemented on silicon wafers. On the wafer, a 500 nm layer of Silicon Nitride is used as a dielectric substrate. On top of this layer, electrically conductive cathodes and anodes are formed in a comb pattern with an aluminium layer. A 1.5 mm by 2 mm area is covered by 20 μm electrodes, with a distance of 20 μm.

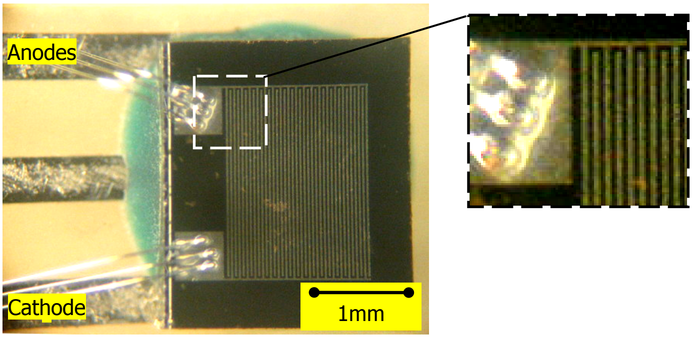


Figure 6-9 Silicon chip for electrolysis test

Testing is carried out with the liquid solidification gripper setup developed in this research. Rather than integrating this silicon chip into the gripper tip as the effective layer for real pick and place operation, the chips are attached to the gripper tip as the target object. With a DC current passing through, the ice contact should break and the chip should fall off. In order to make the electrical connection, the silicon chip is mounted to the top of a fibreglass plate, where the connections are made to the power supply. The connection between the bonding area of the fibreglass plate and the chip is achieved by using three 30 μm wide wires per electrode area.

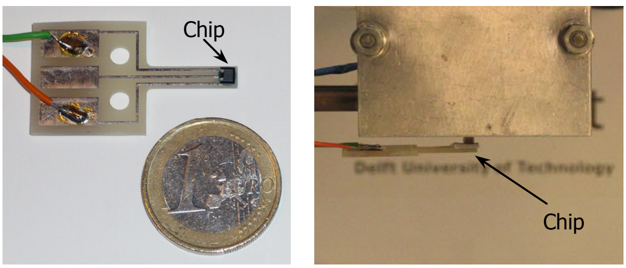


Figure 6-10 (left) Silicon chip mounted on fibreglass; (right) A device is frozen to the gripper

The silicon chip with the fibreglass substrate is frozen to the gripper tip at a temperature of -8 °C, as shown in Figure 6-10. In order to stabilize the ice connection, the freezing process lasts 1 minute. With a voltage of 30 V applied to the electrodes, the chip falls off within 1.5 to 2 seconds. Repeatable results are measured with a single sample chip in further tests [Blom05]. However, the release time achieved by this strategy is not small enough for the purposes of this research work, and offers no reduction in the grip cycle time. The insufficient releasing speed can be explained by the lengthy reaction needed to generate a sufficient amount of bubbles, which results in a decrease of the adhesion force. In order to release the attached part, the contact between the gripper and the part must be entirely separated by gas. With the experimental devices used in this research, the electrolysis process must be continued for longer than 1.5 seconds to achieve this. Further optimization work is needed to shorten the releasing time.

Further tests with tap water and purified water show that the functionality of the chip is sensitive to the impurity. When tap water is used as the gripping intermediate, accumulation of the sediment on the effective area of the silicon chip is observed. At the moment that a chip starts malfunctioning, a visible amount of residue can be detected. With the purified water in use, no stain or imprint is observed on the effective area. The same releasing speed is measured when tap water is used. However, the chip functions better when purified water is applied. It is believed that the sediment or possible corrosion of the electrodes can cause failure in releasing and can shorten the duty cycles of the effective layer.

6.8 Summary

Four types of materials are investigated as potential micro-gripping intermediates. These are water, magnetic-rheological fluid, thermoplastic polymers and thermosetting polymers. The study confirmed the application advantages of water as a gripping intermediate. It is non-poisonous and non-corrosive, clean for the operation, less sensitive to part materials and geometry. A relatively high grip force and contact stiffness can be guaranteed. For the first time, electrolysis is studied as a potential releasing strategy for micro-gripping. Although it is an interesting alternative releasing method, the investigation does not show major advantages in the actual releasing time.

Thermosetting polymers are a good alternative to water as a gripping intermediate, as in theory the liquid-solidification process can take place in a very short time. It is possible to realize very compact gripping devices. Further research efforts are required to develop the ready-to-use polymer.

On the basis of the investigation, water's properties allow it to be a good gripping intermediate. The development of liquid solidification gripping is thus continued with water as the gripping intermediate. Furthermore, the research is focused on gaining a better understanding of the gripping process on the physical principle level. On the basis of this knowledge, efforts are being made to improve the performance of this gripping method, which incorporates shortening the grip cycle time, broadening the application domain, and industrializing the grip principle. The performance of the four types of materials is summarized in Table 6-1.

	Thermoplastic polymers	**Magnetic-rheological fluid**	**Thermosetting polymers**	**Water**
Cycle time	In seconds range	Not tested	Possible in milliseconds range	Possible in hundreds of milliseconds range
Grip force (indication value)	60 mN/mm^2	Not tested	15 mN/mm^2	1 N/mm^2
Operation temperature range	Small range close to room temperature	Small range close to room temperature	Small range close to room temperature	Large range, over 100 degrees from a few tens of degrees below zero
Residue and stain	Large amount	Not tested	Large amount. Possible to improve	No visible residue
Application issue	No obvious application advantages	Toxic, corrosive	Long term polymer development needed	Good gripping intermediate, cycle time must be reduced

Table 6-1 Summary of the performance of gripping intermediates materials

7 Development of liquid solidification gripping system

Following the investigation presented in Chapter 6, three research steps are taken to gain more knowledge of the characteristics of the liquid solidification grip principle with water used as the gripping intermediate. Each step consists of a gripping process analysis, gripper development, prototyping and experimental investigation. These steps are taken in order to (1) proof and study the principle and identify application criteria, (2) optimize the process for short gripping cycle, and (3) approach a fully functional gripping system.

The development and designs are illustrated in sequence. Test results are briefly addressed after each prototype. More elaborate results on the experiments and testing are stated in Chapter 9.

7.1 Proof of the principle and criteria identification

The liquid solidification grip principle, with water used as the gripping intermediate, was introduced in Chapter 4. A number of gripper designs are found throughout literature studies, which basically show the principle works. In [Patent US 5452932], a design of a liquid solidification gripper is described. The design uses semi-circular tubing, which contains liquid nitrogen or carbon dioxide coolant to freeze the target object to the gripper. To release the object, heated liquid is supplied through the tubing. The application of this grip principle is claimed to be applied in textile handling in [Patent DE 4411826C1]. The cooling and freezing process is achieved by using thermoelectric cooling (TEC) components. Comprised hot air is used to release the textile object after being gripped. The same gripping strategy is shown in [Kochan97] and [Patent EP 1319613] by using TEC components in handling meso- to micro- objects. The research claims a grip cycle time of 9 seconds and a grip force of up to 1 N/mm^2 in the operation. In other research [Liu04], micro-objects are handled in aqueous environments with a liquid solidification gripper. The freezing process is achieved with the Joule Thompson throttling effect.

In this research project, a prototype is built as the first step in order to garner a better understanding of the gripping process. These include the freezing and melting processes of the gripping intermediate, water, the accumulation of design and prototyping knowledge that can be transferred for further development, and the identification of key issues for further development by testing and observation of the gripping process.

7.1.1 System description

The gripper implements the essential functions of a liquid solidification gripping device, which are the cooling and heating functions for water freezing and ice melting. The temperature is controlled and stabilized in the range of -10 ˚C to 20 ˚C. The gripper is handled by a robot. Dosing of the gripping intermediate is done manually. A TEC-module was used as the cooling element to change the liquid phase of the gripping intermediate into a solid phase.

A TEC-element is a thermal electric heat pump. The working principle is based on the Peltier-Effect. It consists of a number of thermocouples composed of a semiconductor material. The couples, connected in series electrically and in parallel thermally, are integrated into modules. When current passes through an element, it cools down at one surface and heats up at the other surface. By switching the current direction, the same TEC-module served as the heater to change the solidified gripping intermediate back into a liquid.

In the design and experiments, water was used as the intermediate. The cone-shaped copper gripper sat on a square base, which provided a good heat transfer interface from/to the gripping intermediate to/from the square-shaped TEC-element. A water cooler was employed to remove the heat from the hot side of the TEC-element. The overall gripper configuration is shown in Figure 7-1. The temperature at the TEC hot side and cold side was monitored with two thermistors, which were placed in the positions shown in the figure. The temperature signals are used to control the current flow to the TEC-element with a PI controller.

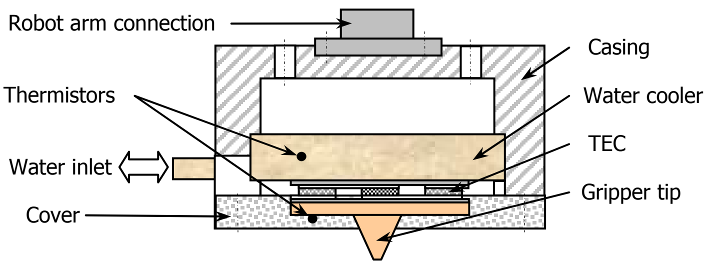


Figure 7-1 Gripper configuration

7.1.2 Experiments and observations

Both quantifiable and visual observational experiments were conducted on the gripper. The first estimation measurement of the grip force was conducted with force dials. The overall adhesion force that can be evoked is relatively large compared with the gravitation of the part or the forces that arise in the assembly process. High values of specific grip force around 1 N/mm^2 were measured. The flexibility with regard to both part material and part geometry is confirmed in the test, which in combination with the high specific grip force, is the main advantage for industrial application.

Experiments show the gripper is able to grip curved surfaces, as shown in Figure 7-2 (left). The metal ball was easily picked up. The strong adhesion force and rigidity of the solid phase makes it possible for the gripper to set the gripping contact a good distance away from the gravitational centre of the target part. This means that the gripper is able to overcome a relatively large bending moment to the gripping operation. As shown in Figure 7-2 (right), a ring-shaped part is gripped with one contact point on its rim. The strong force and the rigidity are also interpreted as a broader alternative of the contact area selection on the part.

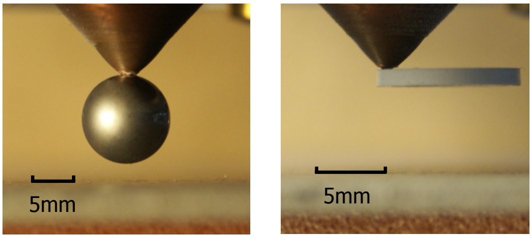


Figure 7-2 (left) Gripper lifting up a large mass, a steel ball;
(right) Gripper picking up an object with a large offset, a ring-shaped part

Target object with different materials and different surface roughnesses were tested. With respect to the influential parameters on adhesion force, the comparable surface roughnesses were employed, but different values of grip force were measured on the different materials. For the same material, a rougher surface leads to a higher grip force, which was shown on all three materials. The grip force increased when the gripping temperature was decreased.

The influence of the part surface roughness on the grip force was tested with glass specimens with surface roughnesses of Ra = 0.01, 0.78, and 1.37 µm, [Lang05]. The force measurements for each surface roughness were performed at temperatures of -3, -5, -7, and -9 °C, with 0.5 µl water used as the gripping intermediate. A waiting time of 2 minutes was given to stabilize the gripping contact. The test results are shown in Figure 7-3.

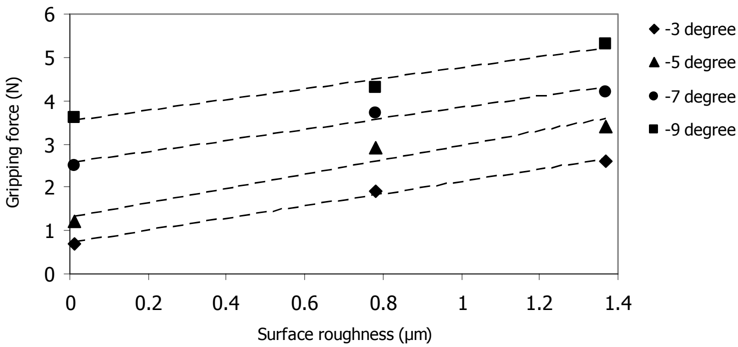


Figure 7-3 Grip force with different surface roughtnesses and temperatures

The figure clearly shows the trend that the grip force increases for contact surfaces with a higher surface roughness. The same trend was confirmed in tests with different materials.

Figure 7-3 also shows that the grip force increases as the gripping temperature decreases. This outcome corresponds with the results achieved by other researchers [Hobbs74]. In Figure 7-4, the effect of the gripping temperature on the maximum grip force is again obvious. The figure shows that the maximum grip forces tend to meet at one point, at a specific low temperature. This suggests that the adhesion strength between the ice and the part will exceed the ice cohesion strength. Thus, when a large tensile force is applied under this temperature, the failure will occur due to the breakage of the ice cohesion bonding. In this condition, the grip force cannot be increased by further lowering the gripping temperature.

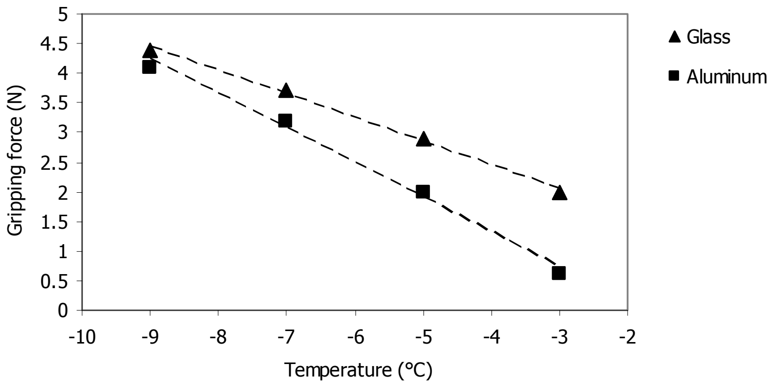
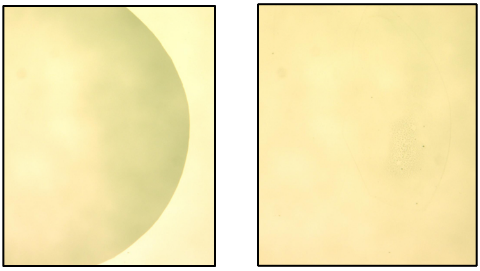


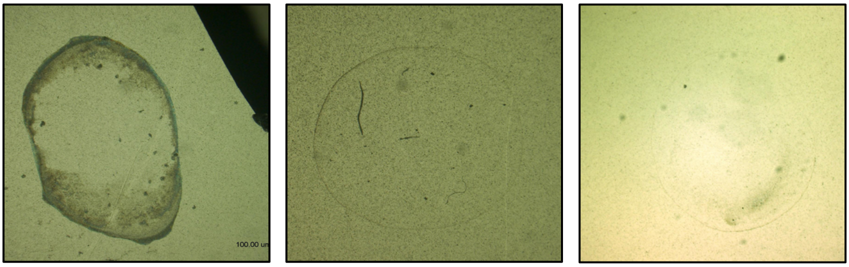
Figure 7-4 Grip force with different materials and temperatures

One of the known application issues is that for certain applications an imprint is unacceptable after the gripping operation. In order to get a better view of how visible the imprint can be, some observational experiments of water evaporation and surface contamination were conducted on a glass surface and a silicon wafer. The results of the surface contamination after water evaporation are shown in Figure 7-5 and Figure 7-6. The imprint after the evaporation of tap water is clearly visible. When demineralized water is used, the surface contamination is no longer visible on the glass surface, but still slightly visible on the silicon surface. A comparison test with HPLC (High Performance Liquid Chromatography) water is performed on a silicon surface. The mark remained visible. It should be noted that the HPLC water has very little impurity and is normally used for wafer cleaning. The results indicate that dust or contaminations in the working environment or originally left on the testing surface could be the cause of the imprint.



Glass substrate with 0.1 µl demineralized water | After evaporation

Figure 7-5 Water evaporation and visibility of the imprint on the glass



Silicon wafer, 0.1 µl tap water After evaporation | Silicon wafer, 0.1 µl Demineralized water After evaporation | Silicon wafer, 0.1 µl HPLC water After evaporation

Figure 7-6 Water evaporation and visibility of imprints on the silicon

7.1.3 Summary

This investigation confirmed the advantages of this grip principle for applications. Good flexibility in gripping with respect to the part geometry and material is observed. A relatively high grip force is measured with the experiments. It indicates that the grip force is influenced by the gripping temperature, part materials and surface roughness of the gripping contact.

The experiment indicates that the grip cycle time is too long to be considered acceptable with this configuration. The cooling and heating are implemented in this design by switching the current direction that flows through a single piece of the TEC-element. Meanwhile, the mass of the gripper tip is relatively large, which requires an excessively large amount of power and time to alternate its temperature between the gripping and releasing temperatures.

The grip cycle time will be optimized in the next development phase.

7.2 Process optimization for shorter grip cycle time

The grip cycle time is one of the essential issues that requires improvement. As defined in Chapter 5, grip cycle time is the time required to establish and end the kinematic relationship between the gripping device and the part to be gripped, without the intermediate move operation. In the interest of industrial application, 1 second per gripping cycle can be set as the typical operation speed. However, the known liquid solidification gripping solution does not cope with this criterion. As a reference, the cycle time for state of the art applications is 9 seconds per gripping cycle [Kochan97].

Improving the grip cycle time is the major goal for this design stage. By closely studying the thermal behaviour of the gripping process and heat transfer between the interfaces of the system, the speed can be shortened with two approaches. One is to refine the structure of the gripping system for a better thermal performance. Another approach is to improve the handling strategy. Both strategies are employed in this prototype design.

7.2.1 Thermal model and process analysis

The gripping scenario in the cooling process can be described with a lumped capacity thermal model, as shown in Figure 7-7. The gripper has a gripping temperature T_{gr}, which is in contact with a water droplet through a contact area A_w. The water droplet has thermal conductivity k_w, mass m_w, volume V_w, density ρ_w, heat capacity C_w, temperature T_w and thickness L. This water droplet is positioned on a part, with a mass m_p, volume V_p, density ρ_p, heat capacity C_p, and temperature T_p. It can be assumed that the water droplet and part have the same temperature T_p. The heat transfer, by means of convection and radiation, are ignored in this model. Furthermore, heat transfer from the table to the part is also ignored.

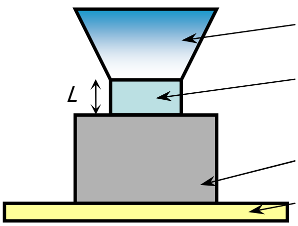


Figure 7-7 Thermal model of the gripping process

The heat change of the part when its temperature is changed from T_0 to T_i is described with:

$$Q_{T_0 \to T_i} = m_p C_p (T_0 - T_i) \cdot \tag{7-1}$$

The time t required to change the temperature of the part (T_p) via the water droplet from room temperature to 0 ˚C (assuming that the intermediate is unfrozen in the process) can be described with:

$$(m_p C_p + m_w C_w)\frac{dT_p}{dt} = -h_c A_w (T_p - T_{gr}) \cdot \tag{7-2}$$

The heat transfer coefficient h_c of the water droplet depends uoon the thickness and the heat conductivity of the droplet:

$$h_c = \frac{k_w}{L} \cdot \tag{7-3}$$

The Equation 7-2 is rewritten as:

$$\frac{dT_p}{dt} = \frac{-h_c A_w}{(\rho_p V_p C_p + \rho_w V_w C_w)}(T_p - T_{gr}) \cdot \tag{7-4}$$

Equation 7-4 is a differential equation for the part temperature as a function of time. With the assumption that T_{gr} is constant, at the initial condition $t = 0$, the temperature response is:

$$\frac{(T_p - T_{gr})}{(T_0 - T_{gr})} = e^{T_c t}, \tag{7-5}$$

with $$T_c = \frac{-h_c A_w}{(\rho_p V_p C_p + \rho_w V_w C_w)}. \tag{7-6}$$

From Equation 7-5, the gripping time t can be described as a function of the gripper temperature T_{gr}:

$$t = \frac{1}{T_c}\ln\left(\frac{T_p - T_{gr}}{T_0 - T_{gr}}\right) \cdot \tag{7-7}$$

The solidification process of the gripping intermediate takes place at the moment its temperature reaches 0 °C. The latent heat of fusion stored in the liquid is released and conducted to the gripper. The freezing time can be estimated with the model of solidification of flat layers, also known as Stefan problem, [Baehr98]. The “Stefan problem” is a transient model that calculates the moving speed of the boundary between the solid and the liquid phase under a heat exchange condition. From the speed model, the time to solidify the entire gripping intermediate layer can be determined. Only one dimensional heat conduction in the perpendicular direction to the gripping contact surface is assumed. The part is assumed to have the same temperature (0 °C) as the water drop. The heat exchange with the table is neglected. The time (t_l) required to solidify the entire water layer of thickness L is:

$$t_l = \frac{h_l \rho_w L^2}{2k_i (T_0 - T_{gr})}(1 + \frac{1}{3}Ph^{-1} - \frac{2}{45}Ph^{-2} + \frac{16}{945}Ph^{-3} - ...), \quad (7\text{-}8)$$

with $$Ph = \frac{h_l}{C(T_0 - T_{gr})}, \quad (7\text{-}9)$$

with k_i as the thermal conductivity of ice, T_0 as the temperature of the boundary between the solid and the liquid phase ($T_0 = 0$ °C), and Ph as the phase transition number.

For Ph>3, the approximation of solidification time (t_l^*) has an error of less than 10%:

$$t_l^* = \frac{h_l \rho_w L^2}{2k_i (T_0 - T_{gr})} \quad (7\text{-}10)$$

From this analytical model, the design parameter of the gripping system can be summarized. In order to minimize the time t for the temperature change, one can fine-tune the following parameters:

- reduce the water volume;
- increase the contact area of the gripper to water droplet, and of the water droplet to the part;
- reduce the thickness of the water film (*i.e.* shorter separation distance);
- increase the temperature difference between the gripper and the part; and
- optimize the geometry of the gripper body to dissipate the energy rapidly from the gripper tip.

According to the above noted summarized issues, the gripper requires a lower temperature in the gripping process to achieve a shorter freezing time. From this analysis, it is clear that the gripper should be equipped with a powerful cooler to adequately lower the temperature. Meanwhile, the gripper requires enough heat conductivity to transfer the heat away from the water and the part. A sufficient amount of gripper mass can also help maintain a constantly low temperature.

The entire gripping process includes the process of freezing the water droplet with a part attached, and the process of releasing the part by melting the water. Having said that, the gripper should be able to alternate the operational temperature in the range of a few tens of degrees in a short cycle. The design as mentioned in the first prototype (a single TEC element used for both cooling and heating) cannot achieve that. This is due to the fact that the mass of the gripper tip is too large for a rapid temperature fluctuation. As another handling strategy, a second actuator (a heater) is introduced into the system, which is dedicated to the melting (heating) function. In such a manner, the gripper contains a cooler together with a large enough gripper tip to perform the gripping process, and a small but powerful heater, to melt the ice at the very moment of releasing.

7.2.2 System description

The gripper prototype is designed to have two TEC elements that clamp a copper gripper plate. The number of TEC elements used in the generation is double that of the first design in order to improve the cooling capacity. At the end of the gripper plate, the gripper tip is formed. An electrical heating plate, a piece of Nickel-Chromium resister, is attached to the gripper tip. This heater is placed at the extreme end of the gripper tip, which actually has contact with the gripping intermediate in the operation. The principle drawing of the gripper is shown in Figure 7-8. The grip surface in the design is 3 mm^2. The gripper is handled by the same robot as used for the first design. Dosing the gripping intermediate is done manually in the operations, [Blom05].

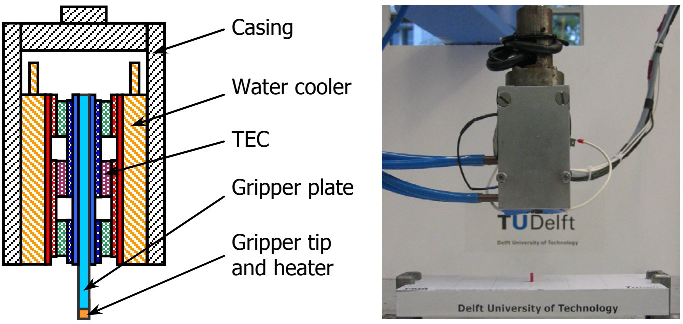


Figure 7-8 Principle drawing and actual setup of the second gripper design

Efforts are made to realize a lower temperature at the gripper tip as one step to improve the operation strategy. TEC-elements are adopted in this development. The maximum temperature difference between the two sides of the TEC-elements is limited by the principle and design, which is up to 70 ˚C for the components selected for this design. Meanwhile, in order to achieve a larger temperature difference, more power must be applied to the TEC element. However, this amount of power also becomes a part of the working load of the TEC. There are designs that stack up TEC elements in an effort to realize a larger temperature difference. This type of design normally results in a very low power efficiency, which leads to a very low cooling speed. In this prototype design, in order to maintain a lower temperature at the gripper tip, two TEC elements are used to increase the cooling power of the system, and a lower temperature cooling liquid is used to cool the hot side of the elements. Water below 5 ˚C is put through the water coolers that are mounted on the hot sides of the TEC elements. The minimum temperature that was achieved at the gripper tip is -28.5 ˚C. As a reference, when tap water is used as the cooling liquid, with the same design configuration, -15 ˚C is the minimum temperature at the gripper tip.

7.2.3 Test

Gripping tests were carried out with plastic objects measuring 6x7x3 mm^3. A minimum gripping time of 0.06 seconds was realized for a single gripping test. The releasing time was recorded as 0.02 seconds. It should be noted that this is a very low grip cycle time that can only be achieved under certain conditions. Firstly, the gripping is tested for single pick and place operations. The cycle time of consecutive gripping operations must be treated differently, which will be addressed in the Section 7.3. Secondly, certain small sized components with low thermal conductivity were applied in the tests. For a more reliable pick and place operation, a grip cycle time of 0.5 seconds can be stated. The test was carried out with the following step diagram, as shown in Figure 7-9. The grip cycle time means the time required to execute the grip step of 1-2 and the release step of 5-7.

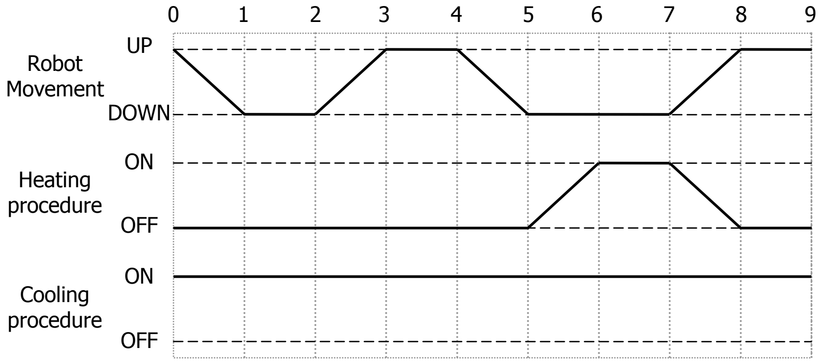


Figure 7-9 Step diagram for grip and release tests with robot handling

It was learned from the test that the gripping process is sensitive to, among other things, the volume of the gripping intermediate used, position of the gripping intermediate with respect to the gripper tip, the gripping temperature, environmental temperature and air flow. The gripping cycle can fluctuate from less than 0.1 seconds to 0.5 seconds, subject to the change of the gripping conditions and environmental conditions.

7.2.4 Summary

The main issue approached in this section is the grip cycle time. A short grip cycle time is achieved by improving the working strategy and the thermal design. A rapid gripping process was achieved at a minimum of 0.06 seconds and 0.02 seconds for releasing processes in single pick and place operations. The grip cycle time is sensitive to the volume and the position of the gripping intermediate, temperatures of the gripper and environment.

In this development, only the key functions of the gripping system, namely freezing and heating of the intermediate, are investigated. The stability of the gripping process, broader applicability with respect to the part materials, and grip cycle time in continuous operations were not studied at this stage. Meanwhile, for industrial applications, the principle needs to be proved as an entire gripping system, which involves further issues than that of simply changing the temperature at the gripper tip. In the next section, the development of a fully functional gripping system is addressed, which aims to investigate the criteria for industrial implementation.

7.3 Fully functional gripping system

With the above stated developments, the grip principle proved its workability, and the gripping cycle has been reduced to less than 1 second. However, an entire gripping system includes more than the functions of establishing and breaking the contact (*i.e.* gripping and releasing functions). The performance of the principle as a complete gripping system has yet to be studied. This final design will demonstrate the principle as an automated gripping system.

An automated gripper prototype for handling small dimensional parts is designed and built. Actual industrial components are used for the handling test. The part feeding function is included in the system design to complete and automate the entire gripping process.

This development step leads to a complete gripping system. In this section, only the concept and the development steps are discussed. The experiment and test performed with this setup are considered to be mature, which will be presented in a separate chapter, Chapter 9.

7.3.1 System description

An overall assembly process can be illustrated with the following "process to function" structure chart, as shown in Figure 7-10. The shaded processes or functions are not of interest in this design.

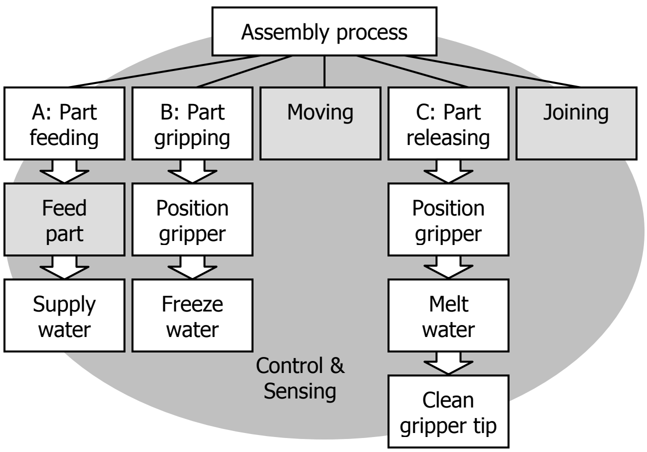


Figure 7-10 Function structure gripping process

The working process of this handling system is composed of A: part feeding, B: part gripping and C: part releasing. Required functions are listed under the processes A, B and C. Water is the liquid that is used as the intermediate between the gripping device and the part.

The gripping intermediate (water) supply is introduced in the part feeding process in this design. In principle, the intermediate can be supplied either to the gripper tip or to the part. Supplying the intermediate to the gripper tip is difficult for this working concept, due to the fact that the gripper tip is constantly cooled to subzero temperatures. The water would immediately be solidified on the gripper tip before it touches a target part. As a result, in this prototype, the intermediate is dispensed on the part, using a separate dispensing system.

After the part is fed, the gripper is positioned just above the part, touching the water, and the droplet is then solidified. In order to achieve this, the gripper tip is kept at subzero temperatures. When the droplet is frozen, the part is attached to the gripper tip and ready to be moved.

After the part is placed in its final position, it is released. This is accomplished with an integrated heating device in the gripper tip, which melts and evaporates the water. In addition to releasing the part, the heating device cleans the gripper by evaporating ice/water left on the tip. At the moment the next part is fed, the temperature of the gripper tip is recovered for the new handling. The entire gripping process diagram is shown in Figure 7-11.

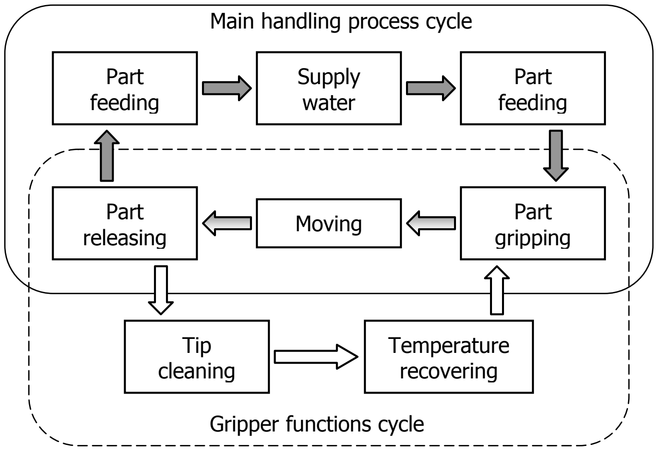


Figure 7-11 The process diagram of the entire gripping system

7.3.2 Thermal design

For industrial applications, the cycle time of a gripping process is an important requirement. It consists of the time required to attach and release the part. The demand on the cycle time is generally in the order of 1 second. Therefore, freezing the droplet with the part must be achieved in less than one second. Industrial diamond parts are used as an extreme application case to test the performance of the gripping system. As an important portion of the cycle time, the freezing time is highly determined by the heat conductivity of the material of the part to be gripped. Diamond parts are excellent heat conductors, with heat conductivity of approximately 2300 W m^{-1} K^{-1}. If this extreme material with excellent heat conductivity can be successfully handled in a reasonably short cycle, the system can also handle parts made from other materials in a comparable or shorter cycle time. In order to freeze the droplet, the top layer of the part must also be cooled down to subzero temperatures. For calculation, it can be assumed that the temperature of intermediate has to reach -5 ˚C. The heat that is removed from the droplet and the diamond part can be calculated with Equation 7-1. In order to cool down a water droplet of 0.1 µl from ambient temperature to ice of -5 ˚C, 43 mJ must be removed. This is a relatively small amount compared to the estimated 540 mJ that must be removed from a diamond part to reduce its temperature from ambient to -5 ˚C.

Because the heat conductivity of diamond is very high and the dimension of the part is relatively small, the lumped capacity assumption can be applied to the part in calculating the necessary gripper tip temperature to attach the diamond to the gripper in less than 1 second. In this calculation, the gripper tip is assumed to have a constant temperature, for the reason that the copper plate has a relatively large thermal capacity and good thermal conductivity. All of the heat is removed through the droplet. The cooling time can be estimated in two stages with Equation 7-7. Firstly, because the thermal properties of water differ from that of ice, cooling the part from the ambient temperature to 0 ˚C and then cooling to -5 ˚C. To freeze the droplet and the part in 0.75 s, the gripper tip must have a temperature of at least -25 ˚C. Earlier studies and tests in this research showed that the gripper body must absorb at least 24 W of heat from the gripper tip in order to keep the temperature at -25 ˚C. This energy is for cooling the droplet and the part, absorbing heat from the heating device, and for heat losses to the environment.

Cooling strategies

Three cooling strategies were considered in this work. Strategy A involved the direct cooling of the gripper body with a coolant of -30 ˚C; Strategy B involved the double-stage cooling with two TEC-elements cooled with water of ambient temperature, and Strategy C involved double stage cooling with one TEC-element cooled with a water-glycol mixture of -10 ˚C. Schematic drawings are shown in Figure 7-12.

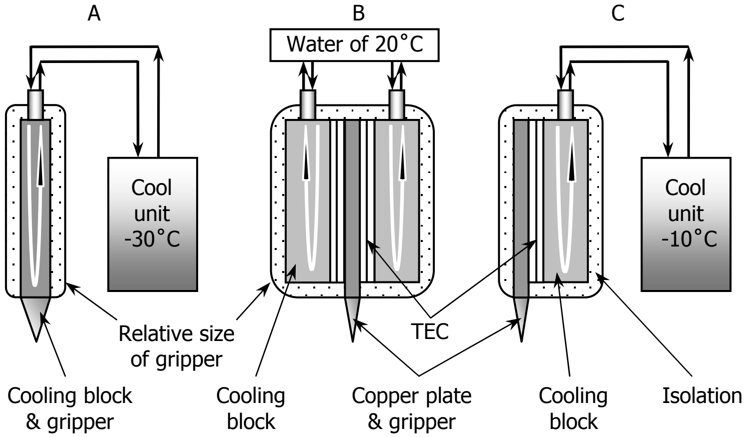


Figure 7-12 Cooling strategies

In the direct cooling method, Strategy A, the gripping device can be made as a solid body with good thermal conductivity. The body contains multiple ducts. A coolant flows through the ducts to cool the gripper to -25 ˚C. When the gripper touches the droplet, heat flows from the part and the droplet, through the gripper body to the cooling liquid. In order to have sufficient heat transfer, a coolant of approximately -30 ˚C is necessary, depending on the cooling area and the heat transfer coefficient. Direct cooling of the gripper body is a very efficient method. The cooling system only needs to remove the heat necessary for the pick and place operations, and some heat lost to the environment. In comparison, the other two strategies use one or two TEC elements. These elements work with energy input, and thus generate heat themselves. As a result, the heat generated by the TEC elements must also be removed. Consequently, the energy efficiency of Strategy A is higher than the efficiency of the other strategies.

The major disadvantage of direct cooling is that a cooling system for coolants of -30 ˚C is relatively complex. In addition, as a practical issue, coolants of -30 ˚C cannot be transported through flexible tubes. This limits the movability of the gripper.

In order to cool the gripper tip to -25 ˚C, the second method, Strategy B, is based on double-stage cooling. Two TEC-elements cool a plate composed of a material with good heat conductivity. The gripper tip is a part of the plate. The plate is clamped between the cold sides of two TEC-elements. The hot sides of the elements are attached to two cooling blocks. The cooling blocks are supplied with water of ambient temperature. When the gripper touches the droplet, heat from the part and the droplet flows through the plate and the TEC-elements to the cooling water. TEC-elements have a certain heat pumping capacity. A zero degree temperature difference between the hot and the cold side of the element generates a maximum heat pumping capacity. On the other hand, the heat pumping capacity is zero for the maximum temperature difference. The gripper tip on the plate requires a temperature of -25 ˚C. The coolant has a temperature of 20 ˚C. This means the temperature difference between the two sides of the TEC-element must reach at least 45 °C. Under this condition, the heat pumping capacity is less than the desired 24 W, which is determined from experiments done with previously mentioned prototypes.

The third strategy, Strategy C, is proposed as a combination of the two strategies mentioned above. To achieve the desired low tip temperature without using a complex cooling system, single TEC-element is a good choice. In order to increase the heat pumping capacity of the element, the hot side of the TEC is cooled with a coolant of -10 °C. In this temperature range, no complex cooling system is required and flexible tubes can still be used. A copper plate is attached to the cold side of the TEC-element. The hot side is attached to the cooling block. Heat from the copper plate flows through the TEC element to the cooling block, and is removed by the coolant. The gripper device is thermally isolated to reduce heat loss and to avoid condensation. The gripper tip, which is a part of the copper plate, sticks out of the isolation layer. This tip absorbs the energy from the droplet and the part.

From this comparison, Strategy C is chosen to establish the system, which has double stage cooling, with one TEC-element cooled with a water-glycol mixture of -10 °C. This strategy allows the realization of a reasonably small gripper unit, and better movability due to the flexible piping.

The following calculations indicate that the capacity of this concept is sufficient. In [Melcor], the equation is given by the TEC-element manufacturer for calculating the cooling capacity (Q_c), as a function of the current and the cold and hot side temperatures (T_c and T_h):

$$\dot{Q}_c = 2N[aIT_c - \frac{I^2 p}{2G} - K(T_h - T_c)G] \Rightarrow T_h(I), \tag{7-11}$$

with N as the number of thermocouples in the element, a as the Seebeck Coefficient, I as the electric current, p as the resistivity, G as a geometric property of the TEC, and k as the thermal conductivity of the TEC-element. Because the cooling capacity (24 W) and the cold side temperature (-25 °C) are known, Equation 7-11 can be rewritten to the hot side temperature as a function of the current in the TEC-element. The voltage (U) for the TEC-element is given in [Melcor] as:

$$U = 2N[\frac{Ip}{G} + a(T_h - T_c)] \Rightarrow U(I) \cdot \tag{7-12}$$

The only variables in Equation 7-12 are the current and the hot side temperature. Due to the fact that the hot side temperature is a function of the current, the voltage of the TEC-element is also. Equation 7-13 gives the heat transfer from the hot side of the TEC-element to the cooling block. It consists of the cold side cooling capacity and the power of the TEC-element:

$$\dot{Q}_{cb} = \dot{Q}_{c} + IU \Rightarrow \dot{Q}_{cb}(I)\,. \tag{7-13}$$

In Equation 7-13, the cold side cooling capacity of the TEC-element is known. The voltage is a function of the current. The heat transfer from the hot side of the TEC-element to the cooling block (Q_{cb}) is also a function of the current. Equation 7-14 gives the heat transfer from the cooling block to the cooling liquid as:

$$\dot{Q}_{cb} = A_{eff} h_c (T_h - T_{coolant}) \Rightarrow A_{eff} h_c = \frac{\dot{Q}_{cb}}{T_h - T_{coolant}}\,, \tag{7-14}$$

with A_{eff} as the effective cooling area. Substitution of Equation 7-13 in Equation 7-14 gives the effective cooling area multiplied by the heat transfer coefficient in the cooling block, as a function of the current of the TEC-element. This function is minimized for a current of 6 A. The effective cooling area multiplied by the heat transfer coefficient is thus 4.5 W/K. The effective cooling area of the cooling block is 3700 mm^2. The heat transfer coefficient depends upon the coolant flow and is approximately 3000 W m^{-2} K^{-1} according to the design calculations. This set of parameters is sufficient to freeze the droplet and the part in 0.75 s.

Heating

After the part is placed in its final position, it must be released. This is accomplished by Joule heating. The tip of the gripper device is covered by a resistance heater. The ice is attached to this heater. To release the part, a voltage is applied to the heater. The generated heat melts the ice and partly evaporates the water. For various applications, it is important that no water remains on the part. The heater can fully evaporate the water in a fraction of a second. Condensation from the environment that solidifies around the gripper tip is also removed by the heater. In a handling operation, when the part is attached to the gripper, the cooling device will continue to cool the droplet and the part, until the part is released. It is assumed that the temperature can reach -20 ˚C at the moment that the heater is switched on. To evaporate the ice, 307 mJ is needed, which is estimated by:

$$Q_{w-evp} = m_w (C_i (T_0 - T_i) + h_{lm} + C_w T_{evp} + h_{levp})\,, \tag{7-15}$$

with $Q_{w\text{-}evp}$ as the heat required to evaporate the water droplet, m_w as the mass of water, C_i as the heat capacity of ice, T_i as the ice temperature, T_0 = 0 °C, h_{lm} as the latent heat to melt the ice, C_w as the heat capacity of water, T_{evp} = 100 °C, and h_{levp} as the latent heat to evaporate the water. Because the heater is situated between the gripper tip and the ice, a part of the heat generated by the heater goes into the gripper tip. Compared to ice, the conductivity of the copper gripper tip is relatively high (2 W m^{-1} K^{-1} and 390 W m^{-1} K^{-1}, respectively). Therefore, most of the heat generated by the wire will flow into the gripper tip. The resistance of the heater R_{wire} is 0.5 Ω and the current I is approximately 9.2 A. According to the following equation for Joule heating, the power Q of the heater is 43 W.

$$Q = I^2 R_{wire} \tag{7-16}$$

A pulse of 0.5 s generates 21 J of heat. A portion of this heat is used to evaporate the droplet. The remainder is absorbed by the gripper or lost to the environment.

The structure of the gripper head is shown in Figure 7-13.

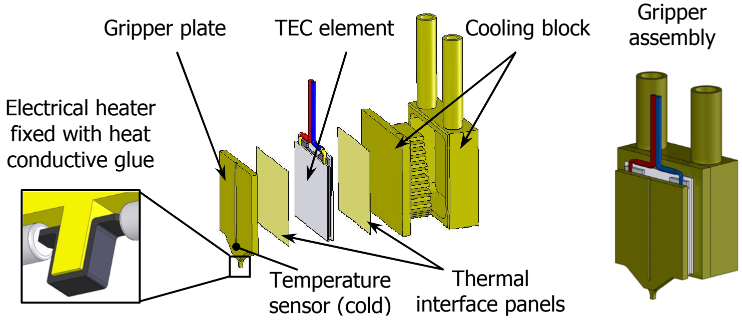


Figure 7-13 The structure of the gripper head

7.3.3 System composition

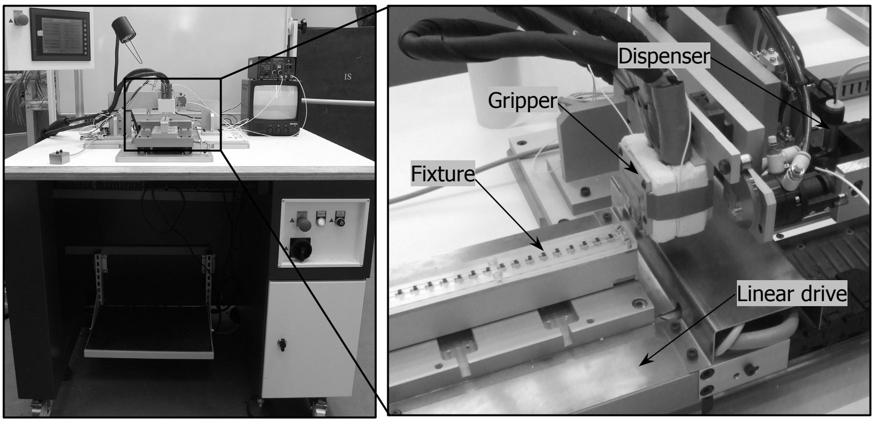


Figure 7-14 (left) Gripping system based on the liquid solidification principle
The entire gripping system on a platform, (right) Closer look on the gripping system

The prototype of the fully functional gripping system is shown in Figure 7-14. On the left hand side, the entire system is presented, which is implemented on a standard industrial platform. On the right hand side, the detailed view of the major functional parts of the gripping system is shown. The system consists of a fixture on a linear drive, the dispenser and the gripper device with the cooling system. The fixture contains a series of parts, 17 in this design, which must be handled. The dispenser and gripper are fixed for horizontal movement. The linear drive moves the parts to the dispenser and to the gripper in sequence. A Micro-drop ® dispenser unit is applied for the water supply. The micro-drop system is based on piezo-driven inkjet printing technology. The dispensing frequency is up to 1500 Hz, with a volume of 180 pl for each drop. Dispensing a typical volume of 0.1 μl takes 0.4 s. The advantage of such a system is that the intermediate doses the part, without contacting it. For handling, a fixed amount of droplets (in the order of hundreds) is supplied to a single part. When droplets are applied to a part, the linear drive positions that part under the gripper. The gripper moves in the vertical direction for the pick and place process. The temperature of the gripper is controlled by a cooling system, whose optimization possibilities were presented in Section 7.3. The gripper device picks up the part, and releases it at a desired position. In order to make the experiments easier, the system is programmed to pick up and release a part at the same location. After releasing, the linear drive brings the next part to the dispenser, and water is supplied to the part. This entire handling cycle is repeated for each part in the fixture. The entire gripping cycle of the small part is shown in Figure 7-15, [Lang07]. Detailed experimental results performed with this gripping system are described in Chapter 9.

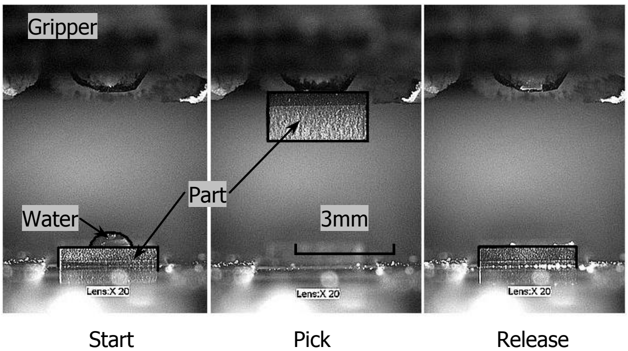


Figure 7-15 Pick and place operations gripper prototype

7.4 Conclusions

The liquid solidification gripping technology, using water as the gripping intermediate, is researched and discussed in this chapter with three specific research goals. The study confirmed the handling flexibility of this grip principle. The application characteristics of this principle are identified via prototyping and experimental analysis. The grip force and influencing parameters are primarily determined. The material, roughness of the gripping contact surface, and gripping temperature influence the specific grip force.

On the basis of the gripping strategy, optimization, and thermal process analysis, the gripping performance with respect to grip cycle time is improved. A gripping cycle of less than 1 second is achieved in handling low thermally conductive component, which brings the principle into the scope of interest for industrial implementations. A minimum grip cycle time of approximately 0.1 seconds was measured in a single pick and place operation. The influencing parameters of the grip cycle time are determined to be the volume of the gripping intermediate, the gripping temperature, the separation distance and the area of the gripping contact.

The industrial applicability is further examined in this chapter by developing a fully functional gripping system. The system offers a platform to examine the application criteria of the liquid solidification grip principle, which relates to feeding or assembly processes and environmental conditions. This gripping system is capable of performing pick and place operations of up to 17 cycles continuously and automatically. In the following 2 chapters, the thermal model of the last gripping system and in-depth experiments on the gripping performance of the system are presented.

8 Thermal process modelling

Section 7.3 indicates that the gripping time is one of the key issues to be studied. The thermal process of the gripping operation is the essential point for improving the grip cycle time. Both finite modelling and analytical methods are applied throughout the development and prototyping processes.

In Chapter 7, analytical means are applied to analyze the general thermal behaviours of the gripping system, including the energy consumption and cooling time. The analytical analysis is performed with certain simplification assumptions. For instance, the part is considered as lumped capacity, the temperature of the gripper tip is assumed to be constant, and the heat exchange with environment is neglected. The analytical calculation is a valuable system development tool. However, it does not provide information of this transient process in detail.

The finite element model addressed in the following sections is dedicated to the thermal process that occurs at the gripper tip in a more precise method. The model provides an inside view of the gripping process with respect to its thermal behaviour. With boundary conditions that are more comparable to the actual condition, it is expected to produce a more accurate estimation of the gripping process, and the grip cycle time. With detailed geometrical information, the thermal process that occurred at the gripping contact can be better simulated, including the temperature distribution in the gripper tip, gripping intermediate and the part, and the thermal influence of the material of substrate. Further process optimizations and principle developments can be conducted with the support of these detailed simulation results. The finite element model also allows for predictions to be made for more general applications. The model can be used as a gripping process defining tool for specific gripping operations. It helps in the selection of a gripping temperature, substrate or part holder, while also providing an estimation of the grip cycle time.

The structure and the boundary conditions are firstly described; following that the modelling process and methods are explained in detail. The thermal behaviour of the gripping as shown by the modelling is concluded at the end of this chapter.

8.1 Geometry of the model and boundary conditions

A software package (COMSOL) with a multiphysics module is selected to simulate the thermal process. The geometry of the final prototype of the gripper is used to construct the finite element model. Meanwhile, comparable temperatures that are used in real gripping processes are applied to the simulation. A few geometrical and construction simplifications, as well as thermal assumptions, are implemented into the modelling process.

Externally to internally, as shown in Figure 8-1, the structure of the gripper prototype includes a thermal insulation shell, a cooling block, 2 pieces of thermal interface panels, a piece of TEC element, and the gripper plate with gripper tip at the end. At the gripper tip side, there is a piece of electrical heater fixed with a thin layer of thermally conductive glue. In a gripping operation, the gripper tip, which is wrapped in the glue and heater, makes contact with a target part via a liquid bridge. In the operation, the target part is placed on a certain substrate.

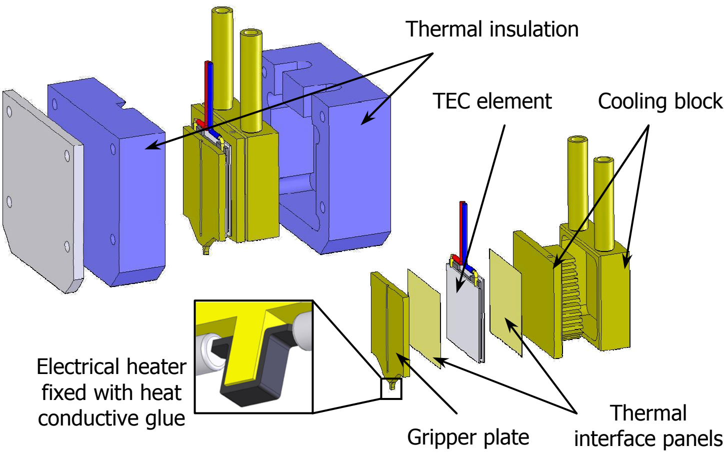


Figure 8-1 Exploded view of the gripper design

The model only includes the critical components necessary to execute the analysis, as shown in Figure 8-2. The gripper plate serves as a cold object and a thermal buffer to subtract heat rapidly from a part to establish the gripping in a minimal amount of time. Meanwhile, it must emit a portion of energy produced by the heater in the releasing process. The dynamic behaviour makes the component an important part for modelling. In a gripping actuation, the electrical heater and the fixing glue make the actual contact with a target part. Meanwhile, the heater operates as the releasing actuator for the system, which also influences the cycle time. The water droplet and target part are the essential parts to be modelled in the analysis. The volume of the droplet and its dimension affect the gripping cycle. When the gripping operation begins, the target part is placed on a certain substrate. In a small scale operation, the heat transfer between the part and the substrate is significant. The TEC element, together with the cooling block, is the cooling actuator for the gripping operation, which are essential for the actual operation. They operate under a constant low temperature. This enables the simplification of the two components with thermal interface panels as the boundary conditions of the gripper plate. The insulation shell can be replaced with a set of boundary conditions for the same purpose. In summary, the model contains the gripper plate/tip, glue, heater, water droplet, part and the substrate. The rest of the components are represented with boundary conditions.

The geometry of the model is defined to match the exact dimensions of the gripper plate, water droplet, and the target part. The model is built in a 3D configuration. In order to maximize the computation efficiency, only half of the system from its symmetrical centre is modelled. For simplification, the water droplet is modelled in a cubical shape, rather than a cylindrical shape. In this manner, the modelling components have more closely matching geometries, which eventually prevent the possible calculation errors that may occur in the meshing process. Different material parameters and boundary conditions are given in steps to the group of water elements in order to simulate its liquid state, phase transition, and solid state.

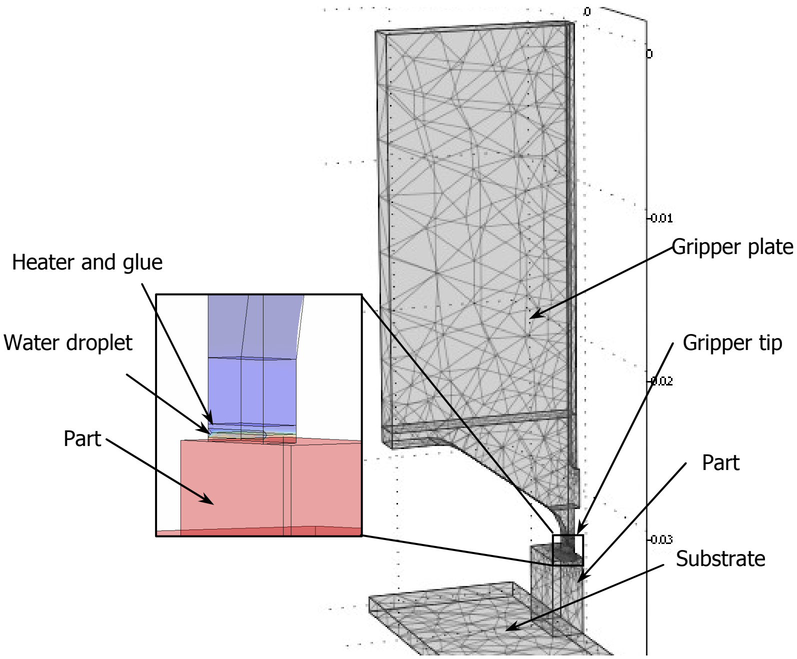


Figure 8-2 The geometry and mesh of the model of the gripper in the operation

The heat transfer conditions of the model are defined according to the actual operating conditions of the gripper prototype. Having said that, the actual heat transfer or temperature conditions that are less influential on the gripping contact are replaced with constants or simplified functions. For instance, the temperature fluctuation of the TEC elements are neglected, which results in a constant temperature condition on the gripper plate. The thermal insulation shell is replaced by a convective heat transfer condition, as stated in this section. The simplification step also aims to maximize the computation efficiency. The heat transfer of the actual gripper prototype is summarised in Table 8-1.

Heat transfer between		**Heat Transfer type**
Gripper plate (tip)	TEC element	Conduction
Gripper plate (tip)	Insulation	Conduction
Gripper plate (tip)	Surroundings	Convection, Radiation
Gripper plate (tip)	Glue	Conduction
Glue	Surroundings	Convection, Radiation
Glue	Droplet	Conduction
Glue	Wire	Conduction
Wire	Surroundings	Convection, Radiation
Wire	Droplet	Conduction
Droplet	Surroundings	Convection, Radiation
Droplet	Part	Conduction
Part	Substrate	Conduction
Part	Surroundings	Convection, Radiation

Table 8-1 Summary of heat transfer types

Thermal radiation is a highly nonlinear factor on the general heat transfer, which is proportional to the fourth-order of temperature. For temperatures in the range of -30 °C to 25 °C, the radiation flow is very small compared to the convective or conductive heat transfer. It is negligible, and therefore, omitted from the modelling in the following process.

Convective heat transfer also insignificantly contributes to the general heat flow of the system. In evaluating the gripper configuration, only the natural convection to air is included. The convective heat transfer coefficient of air has the value of 3~25 W m^{-2} K^{-1}, where 3 W m^{-2} K^{-1} is for absolutely still air. In examining the operating conditions of the prototype, the convective heat transfer coefficient is set as 10 W m^{-2} K^{-1}.

The insulation shell of the gripper is not physically modelled. Instead, it is presented as a convective heat transfer boundary condition. The convective heat transfer coefficient is estimated as 4.01 W m^{-2} K^{-1}, subject to the operating conditions.

The major parameters of the model are summarized in Table 8-2.

Material properties →	**Density *ρ* (kg m^{-3})**	**Specific heat *Cp* (J kg^{-1} K^{-1})**	**Thermal conductivity *k* (W m^{-1} K^{-1})**	**Volume *V* (10^{-9}m^{3})**	**Latent heat h_l (J kg^{-1})**
Gripper and gripping intermediate					
Insulation	--	--	0.02	--	--
Copper	8960	386	400	--	--
Glue	600	500	6	--	--
Heater	4000	400	400	--	--
Water	1000	4200	0.58	0.1	3.34×10^{5}
Ice	900	2100	2.18	0.1	--
Part					
Plastic	2200	1050	0.24	4x4x5 and 3x2x1.5	--
Diamond	3520	510	2000	4x4x5 and 3x2x1.5	--
Substrate					
FR4 (PCB)	1900	1369	0.3	--	--
Hardmetal	15000	220	110	--	--

Table 8-2 Material properties used in simulation [Mills99], [Moran98]

8.2 Modelling process and method

The simulation is performed with one model in 4 consecutive steps. In order to simulate the 4 thermal processes of a gripping operation, different material parameters, boundary conditions and initial conditions are applied to the single model in 4 steps. In the 1st modelling step, the water is cooled to its melting temperature. In the 2nd modelling step, the water is then solidified and latent heat is subtracted. The gripping is established at the moment the entire droplet reaches subzero degrees Celsius. In the releasing process, as the 3rd modelling step, latent heat is added to the ice. The part is released at the moment the top layer of ice is fully melted. In the last process, the 4th modelling step, the gripper recovers its low temperature for the next gripping. All 4 modelling steps are repeated under different meshing conditions to confirm that converging results are achieved.

The simulation begins at the initial condition, summarized in Table 8-3, whereby the gripper plate has a temperature of -30 °C, and the gripper tip and heater have a temperature of -25 °C. The target part and substrate all begin at room temperature of 22 °C. A gripping temperature of 0 °C is set as the end temperature for the cooling model, which is set for the water droplet at the outermost points by the object side. Furthermore, 0 °C is used as the initial condition for the heating simulation. The actual performance of the heater is unknown for the process, due to its extremely rapid response. It is therefore assumed that the heater has a steady temperature of 150 °C, when the heating simulation begins. This simulation step stops at the moment the entire water layer at the gripper side reaches 0 °C.

Sub-domain	**Initial temperatures [K]**		**Constraints**
Gripper (body)	T- Cooling	243.15	The surface contact with TEC is 243.15 K. The temperature of the rest is free to change.
Gripper tip	T- Tip-Initial	248.15	Temperature is free to change.
Glue	T- Tip-Initial	248.15	Temperature is free to change.
Heating wire	T- Tip-Initial	248.15	Temperature is free to change.
Droplet	T- Surrounding	295.15	Temperature is free to change.
Part	T- Surrounding	295.15	Temperature is free to change.
Substrate	T- Surrounding	295.15	Only the bottom surface is 295.15 K. The temperature of the rest is free to change.

Table 8-3 Initial temperature conditions of the simulation

To simplify the model, latent heat is added and subtracted to the water droplet and simulated with separate models. It should be noted that the parameters of water and ice are different. A step function should be implemented in the model to change the properties at 0 °C. However, this causes discontinuity in the simulation process. To avoid this discontinuity, a standard "smooth" function from COMSOL is utilized, which allows the parameter to continuously change within a small zone. The tetrahedral elements are applied in creating the 3D meshing of the model.

8.3 Thermal behaviour and results

The major goal of this model is to simulate the material and geometry dependent behaviour of the grip cycle time. Parts and substrates made from materials with large differences in their thermal properties are selected for study. Specifically, parts made from diamond and plastic, built in two dimensions are used in the model. The materials for the substrates in the model are PCB Woven glass and epoxy (FR4) and hardmetal. In total, this produces 8 material and geometry combinations for the simulation. The results are presented in 4 consecutive modelling steps.

The time required in order to cool a 0.1 µl droplet with different parts and substrate combinations under normal mesh conditions are summarised in Table 8-4, with the units in second (s). The temperature recovery process of the gripper after the heating and releasing does not involve the droplet, part or substrate.

Cooling process in time (s) 22 °C to 0 °C		Substrate	
		FR4	Hardmetal
Part	Plastic 4x4x5 mm^3	0.027	0.027
	Plastic 3x2x1.5 mm^3	0.026	0.027
	Diamond 4x4x5 mm^3	10.38	∞
	Diamond 3x2x1.5 mm^3	1.10	∞
Cooling process in time (s) Subtract the latent heat, 0 °C		Substrate	
		FR4	Hardmetal
Part	Plastic 4x4x5 mm^3	0.054	0.054
	Plastic 3x2x1.5 mm^3	0.052	0.052
	Diamond 4x4x5 mm^3	0.001	N.A.
	Diamond 3x2x1.5 mm^3	0.01	N.A.
Heating process in time (s) Add the latent heat, 0 °C		Substrate	
		FR4	Hardmetal
Part	Plastic 4x4x5 mm^3	0.006	0.006
	Plastic 3x2x1.5 mm^3	0.007	0.007
	Diamond 4x4x5 mm^3	0.006	N.A.
	Diamond 3x2x1.5 mm^3	0.006	N.A.
Recovering process Gripper only, 0 °C to -25 °C		0.073	

Table 8-4 Simulation results of the thermal process time with different combinations (Unit: s)

As a validation step, the modelling results are compared with the experimental observations. The simulations show good correlation with the experiments that are performed with the same target objects and gripping substrates. The experimental results are described in Chapter 9. The comparisons of modelling and experimental results are presented in Section 9.1.1 and Section 9.1.4 with respect to plastic part gripping and diamond part gripping.

Three issues, namely part material, part dimension, and substrate material, are modelled, and summarised in Table 8-4. The modelling results show that the total gripping time is predominantly influenced by the thermal conductivity of the part. Parts with lower thermal conductivity result in shorter gripping times. Parts with higher thermal conductivity have longer handling times.

For objects with lower thermal conductivity, the grip cycle time is less sensitive to the dimensions of the object. The reason for this is that the object is cooled more locally near the gripping contact point and less heat needs to be subtracted.

The property of the substrate has a more obvious influence on the grip cycle time in handling parts with higher thermal conductivity. Because of the high thermal conductivity, in order to establish the grip force, more heat must be removed not only from the target object, but also from the substrate. When increasing the size of the object, the area of part to substrate contact increases. More heat then flows to the gripper tip via the target object, which results in a longer gripping time. As a design rule, it can be concluded that in order to handle higher thermally conductive parts, a low thermally conductive substrate is needed.

With respect to the analytical analysis, the finite element model clearly indicates that, as shown in Table 8-4, in addition to the part properties handling environment, the properties of the substrate must also be considered as important parameters in gripping system development and application. The finite element model creates the possibility of investigating the detailed freezing process and temperature distribution. The model provides a means to predict the operational situations of larger varieties of part geometries and materials. The outcome can support the performance optimization of the gripping system in future work.

9 Test and experimental validation

Experiments are performed on the gripper setups to determine the process window of this grip principle. Grip cycle time and grip force are specifically subjected to more quantified tests with a selected number of part material, part dimension and temperature combinations. As discussed in Chapter 8, there are good reasons to assume these parameters to be the most dominant parameters with respect to grip cycle time. The second and the final prototypes, as addressed in Sections 7.2 and 7.3 respectively, are used as the major testing devices. Demineralised water is used as the gripping intermediate in all experiments.

Firstly, the experimental investigation of grip cycle times is illustrated. The geometrical similarity between the analysis models and the experimental implementation makes it possible to compare and validate the results. Secondly, the tests of grip force are addressed following a brief inside view of the grip force at the intermolecular level. The forces were examined with a number of samples, made from various materials with different surface properties. On the basis of the experiments and observations, several determinant application criteria are summarised at the end.

9.1 Test of grip cycle time

A general gripping operation, based on the liquid solidification principle, can be segmented into the following: dispensing the gripping intermediate, approaching and positioning, establishing the grip force, object transfer, and breaking the gripping contact. In this sequence, the time required to complete approaching, positioning and transferring are not included as part of the grip cycle time. Although intermediate dispensing is an essential action required to perform the gripping operation, it is normally scheduled as a simultaneous step to establishing or breaking the gripping contact. Therefore, the grip cycle time in this discussion contains only the time required to establish the grip force, (or “freeze”), and to break the gripping contact, (or “melt”).

The grip cycle time is influenced by the operational temperature of the gripper body, the materials and the dimensions of the target object, the substrate material, and the volume of the gripping intermediate in use. The performance is depicted with experiments. There are definitely more aspects that can vary the length of a gripping cycle, including the material of the gripping intermediate, and the geometry of the target objects. However, they are minor issues with respect to the goal of this research, and are therefore not addressed in this set of dedicated experiments.

Within this series of experiments, time, (*e.g.* cycle time, freezing time), is controlled and clocked by the control system of the gripping setup; the values are adopted to present the experimental results. The temperature, (*e.g.* the gripping temperature), is measured and close-loop controlled with the sensors and regulating circuit of the gripping setup.

9.1.1 Rapid gripping realized within a single operational cycle

A time of 0.1 seconds for completing an entire grip and release process was recorded as the quickest gripping cycle in the research. This result is a major breakthrough with respect to the handling speed in comparison with the state of the art research into liquid solidification based gripping.

Single pick up and place operation cycles were tested with the second laboratory prototype. The gripper is mounted and handled with a robot. Target components are made from plastic, with a thermal conductivity of between 0.2 $Wm^{-1}K^{-1}$ to 0.3 $Wm^{-1}K^{-1}$. The gripping temperature is set to between -25 ˚C to -30 ˚C. A volume of 1 to 5 μl demineralised water is used as gripping intermediates. A total gripping cycle time of between 0.1 seconds to 0.5 seconds is achieved where the freezing time is between 0.06 seconds to 0.3 seconds, and the heating time is between 0.02 seconds to 0.2 seconds. In Table 9-1, these experimental results are compared with the finite element modelling results presented in Chapter 8. Although this finite element model is built with respect to the design of the last gripping system, because of the very comparable geometry and equivalent thermal conditions between the two prototypes, the model is applicable for the comparison. As expected, comparable results of the processing time are received from the simulation and laboratory test. The minor time difference between the modelling and the experiment in the gripping process can be caused by the instable actual operational temperature of the gripper, positioning accuracy of the gripper, the specific condition of the gripping contact, and other unpredictable changes during the process. The releasing time in the modelling is calculated on the basis of ideal construction of the gripper and the specification of the heating device. However, due to the uncertainty of the characteristics of the heating elements, and manual assembly of the heating system in the experimental setup, the performance of the releasing process more obviously differs from the modelling prediction.

Gripping process time (s) (Freezing process time)	FR4 substrate		Hardmetal substrate	
	COMSOL	Experiment	COMSOL	Experiment
Plastic part 4x4x5 mm^3	0.081	0.06 (min)	0.081	0.06 (min)
Plastic part 3x2x1.5 mm^3	0.078	0.06 (min)	0.079	0.06 (min)
Releasing process time (s) (Heating process)	FR4 substrate		Hardmetal substrate	
	COMSOL	Experiment	COMSOL	Experiment
Plastic part 4x4x5 mm^3	0.006	0.02	0.006	0.02
Plastic part 3x2x1.5 mm^3	0.007	0.02	0.007	0.02

Table 9-1 Comparison of modelling and experimential results with plastic components

The results in the above noted experiments are obtained under strict operational boundary conditions. The part must correctly align with the gripper tip, with a minimum distance between the grip surface and the gripper tip. The gripping intermediate is manually applied to the target part. The gripper must be given adequate time to cool down. The tests are performed in order to measure the operational time of every individual gripping cycle. However, for industrial use, it is important that multiple gripping operations can be performed continuously. This is more difficult than a single pick and place operation because when a part is released by locally heating the gripper tip, a relatively large amount of heat flows into the gripper. The gripper needs time to recover before the next part can be gripped.

The cycle time for a continuous gripping operation is determined with the final prototype, given that it is designed to run automatically for multiple gripping cycles and has better positioning accuracy. Experiments were carried out in such a way that one test contained 17 automated and continuous pick and place operations under certain parameter settings. The same test is repeated multiple times. The experiments are carried out on a shop floor in an open environment, [Lang07]. Three important parameters influence the grip cycle time and are tested individually. These are the temperature of the gripper tip, the material combinations, and the volume of the droplet.

9.1.2 Influence of the gripping temperature

When a continuous gripping test is conducted under certain parameter combinations, both successes and failures occur. The reliability of the gripping is introduced to validate the parameters. The only set of parameters validated for analysis is the one that results in not more than 1 failure per 17 continuous pick up and place operations. For testing of the relationship between the gripping temperature and the cycle time, multiple experiments are performed with varying lengths of time. In using the defined reliability condition, only the time length that ensures not more than 1 failure out of 17 pick and place operations is recorded for cycle time analysis. Figure 9-1 shows the results of 5 different experiments carried out in order to determine the influence of the gripper temperature on the cycle time. The temperatures ranged from -12 ˚C to -36 ˚C, as set points, at the sensor spot in the gripper. Every data point in the graph represents a result of 17 sequential pick up and place operations. For this set of experiments, a droplet of 0.1 µl is used to pick up the parts. Heating time is predefined to be between 0.5 seconds and 0.3 seconds. The target part is composed of diamond. Failure rate is used to indicate the reliability of the gripping process under a certain condition.

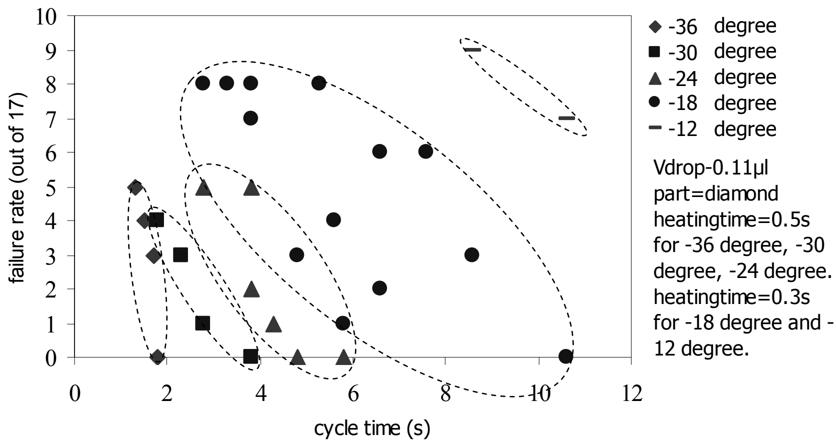


Figure 9-1 Grip cycle time measured against gripping temperature, with failure rates as reference [Warner07]

It is evident that lower gripping temperatures result in a shorter grip cycle time, with higher success rates of handling operations. With a gripping temperature of -36 ˚C, a grip cycle time of 1.8 seconds is achieved, with a failure rate of less than 1/17. A further reduction of the cycle time gradually increases the failure rate. The same trend is observable in all test results.

The data points of the grip cycle times with lower temperatures indicate less spread than that of the higher temperatures. In one aspect it shows the clear trend of the gripping cycle changing under different gripping temperatures. In another aspect, the less spread data also implies that the influences from the environment, including temperature changes, air breezing, condensation, have less effect on the handling process. The gripping process with lower temperatures is more stable and reliable. The higher gripping temperature increases the randomness of the handling process. Numerous experiments were conducted with temperatures of under -18 ˚C to prove this effect. A small change of the environmental conditions, (*e.g.* slightly breezy air, a small change of room temperature, the proximity of people), can cause failure of the gripping operation at the higher operating temperatures.

In using the reliability condition defined above, a figure can be drawn for the reliable cycle time as a function of the gripper temperature, as shown in Figure 9-2, [Warner07]. The freezing time of the entire gripping cycle is compared with the thermal model described with Equation 7-7 in Chapter 7, as depicted in Figure 9-3.

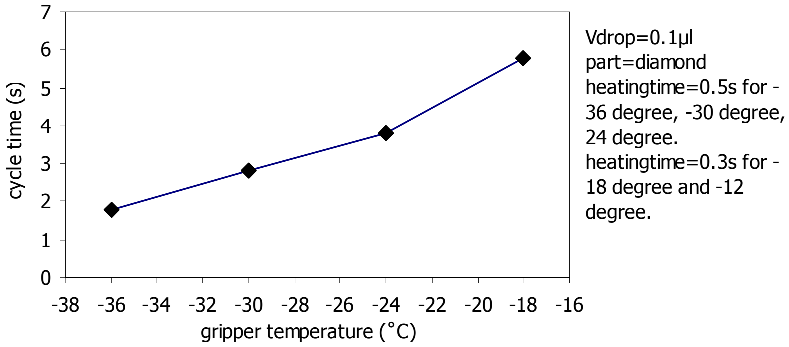


Figure 9-2 Grip cycle time as a function of gripping temperature, with less than 1/17 failure

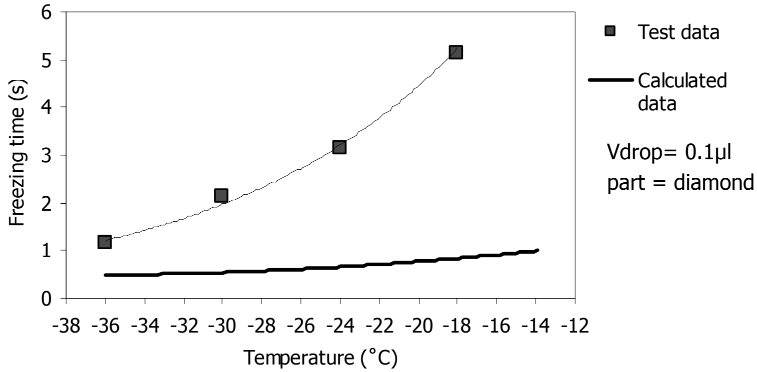


Figure 9-3 Comparison of tested results and theoretical model of freezing time with respect to gripping temperature

Figure 9-3 shows lengthier freezing time results are measured in experiments than in analytical calculations, which can be explained by several factors. The gripping temperature of the experiments is measured with a thermocouple close to, but not on, the gripper tip. The real temperature of the gripper tip is higher. In the theoretical model, the temperature of the gripper tip is assumed to be constant, which changes in the actual gripping operation. Having said this, the actual freezing time is expected to be longer than the analytical calculation. The assembly errors of the gripper can considerably extend the grip cycle time; especially the positioning error of the heater on the gripper tip gives large influence. Several environmental influences are not taken into account in the analytical calculations. The heat loss to the environment is not taken into account in the analytical model. When the gripping process uses more time, it results in more heat exchange between the gripping system (gripper-object-substrate) and with the environment. This extra heat flow from the environment extends the grip cycle time in the actual handling operation, [Warner07]. Meanwhile, as the processing time gets longer, the influence becomes more obvious, thus the difference between experiments and analytical modelling becomes larger.

9.1.3 Influence of thermal conductivity of the target part

The thermal conductivity of the target part obviously influences the grip cycle time. In order to freeze a droplet on a more thermally conductive part, a large portion of the part must be cooled down. More heat flows through the droplet to the gripper in the freezing process, which results in a longer freezing time. A thermally low conductive part can be cooled down more locally, which makes the droplet solidified in a relatively short time. As an extreme example, the gripper prototype in the final design is incapable of gripping the sample diamond objects from a metallic substrate. In Chapter 8, the FEM analysis showed a gripping time of longer than 10 seconds for a 3x2x1.5 mm^3 diamond part on a metal substrate. However, the gripping process cannot be achieved in an actual handling operation. Eventually, the water droplet remains in the liquid phase at the contact interface. In contrast, the handling of a plastic object is not sensitive to the material of the substrate. Figure 9-4 illustrates the difference in temperature distribution in transient states of parts with different thermal conductivities, [Lang07].

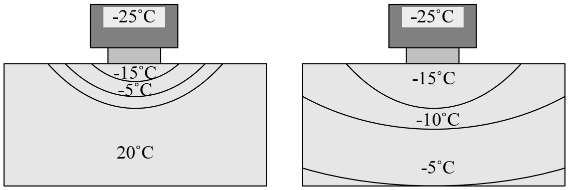


Figure 9-4 Schematic indication of temperature distribution in transient state for parts with low and high thermal conductivity, respectively

Quantified measurement results of handling the diamond part and the plastic part are shown in Figure 9-5. In the graph, only the freezing time of the gripping process is presented, as two different heating times are adopted for releasing the two materials. A heating time of 0.5 seconds is applied for releasing a diamond object, and 0.2 seconds for the plastic object, which constitutes only 40% of the time for diamond part. A clear time difference between handling the two materials can be seen from the graph. A grip cycle time of 0.7 seconds to 0.8 seconds is achievable for the plastic objects.

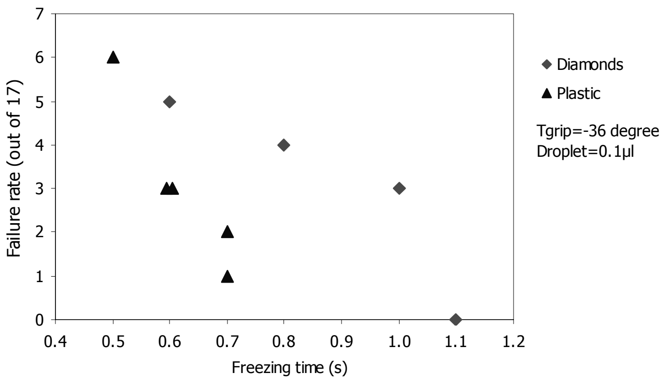


Figure 9-5 Freezing time in gripping the diamond part and the plastic part

In principle, shorter grip cycle times can be expected with plastic parts. The part fixture in the final gripper prototype is designed for the diamond parts, as the plastic parts do not fit properly. Furthermore, the plastic parts have a much lager geometrical deviation, which causes inaccuracies in positioning and processing. Consequently, the gripping is less reliable and results in longer freezing times. Upon closer examination of the failed pick and place operations, it is discovered that an ice layer actually forms on the part. This fact indicates that the gripping connection between the gripper and the part is established. However, this connection is broken when lifting the part out of the fixture, due to the geometrical mismatch. If the failures caused by mismatched geometries are neglected, the gripping operation is achievable within 0.5 seconds. The FEM analysis described in Chapter 8 showed the gripping cycle tim for a thermally isolative part to be approximately 0.1 seconds. Results in this order are eventually achieved in experiments with the second gripper prototype.

9.1.4 Influence of the gripping intermediate volume

Choosing the proper amount of the gripping intermediate in the application is one of the essential issues. It is the ultimate component in the gripping system that physically forms the gripping contact. From a mechanical aspect, it establishes the grip force and serves as the thermal bridge for the heat transfer from target object to the gripper. An appropriate volume assures a rapid solidification process, and thus a short gripping cycle.

Cycle time tests are performed with 5 different amounts of water. The same separation distance between gripper and target object is used for all tests. The above mentioned experiments proved that a gripping temperature of -30 °C delivers a short grip cycle time and a stable performance. Therefore, this temperature is adopted for the following experiments.

With respect to the experiments presented in this section, certain optimization steps have been applied to the final gripper prototype, which include changing the heating unit attached to the end of the gripper, improving the thermal connection between the heating and the cooling units, and refining the surface property of the gripping tip. As one of the important consequences, the gripper performs better than previous experiments. The grip cycle times are generally reduced under every gripping temperature. Thus, the following stated grip cycle times are approximately 30% shorter than the results previously obtained.

Figure 9-6 shows the measurement results with diamond objects as the target objects, wherein the dotted lines indicate the trend of grip cycle time. A larger droplet forms a larger contact area to the object, which requires a longer heating time to melt the entire contact to release the part. The major time difference occurs at the freezing time. Both smaller and larger volumes result in extra time required to establish the grip force.

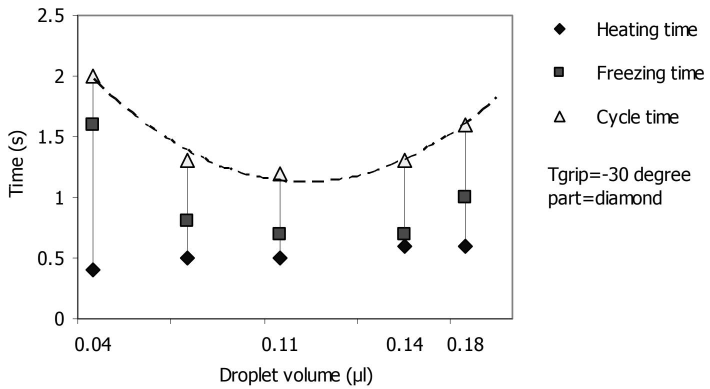


Figure 9-6 Experimental results of gripping cycle as a function of droplet volume

From the analytical model, it is understandable that a smaller volume is preferable for reducing the gripping cycle, since this amount of liquid needs to be solidified. However, in the freezing process, a part of the target object is also cooled and eventually reaches below zero degrees Celsius. In this thermal process, the amount of heat from the object is transferred to the gripper via the gripping intermediate. In this configuration, a thinner film and a larger contact area creates a better thermal contact. The amount of energy that needs to be absorbed from the part is much greater than that required to freeze the small droplet. Given that a fixed distance between the gripper tip and the object is chosen for all tests, the larger droplet actually forms a better thermal contact. When the volume of water is too small to form a sufficient thermal contact area to cover the entire surface of the gripper tip, the grip cycle time becomes longer. The extra volume of water at the contact interface, as shown in Figure 9-7, does not increase the thermal contact area. Instead, it adds to the absolute volume of droplet that must be solidified. As a consequence, the grip cycle time is extended.

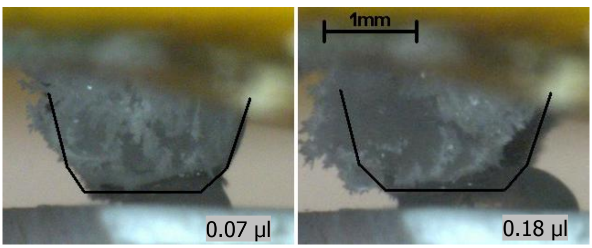


Figure 9-7 The formation of the water film between the gripper tip and the object

The experimental tests with diamond components are compared with the modelling results, as shown in Table 9-2. The gripping process with larger sized diamond components require times of longer than 10 seconds in modelling results. However, successful gripping operations did not actually occur in experiments. Gripping of the smaller diamond parts were achieved with a low heat conductive substrate in the experiments. The minimum processing time for gripping in the tests is slightly shorter than the outcome from modelling. Multiple reasons can be cited for causing this difference. Among others, the performance difference between the actual gripping system and the computer model, the non-uniform processes of the ice-forming on the contact surface are expected to be the most important reasons. Meanwhile, the experimental results of the gripping time deviate from 0.7 seconds to more than 1 second. The modelling result falls within this data spread. The heating element of this gripper is manually fixed to the gripper tip with thermally conductive glue. There are uncontrollable factors in this assembly process. In addition, there can be considerable errors in the estimation of the actual energy consumption of the heating element in its short active time. Thus, the releasing time in experiments differs considerably from the modelling results.

Gripping process time (s) (Freezing process time)	FR4 substrate		Hardmetal substrate	
	COMSOL	Experiment	COMSOL	Experiment
Diamond 4x4x5 mm^3	10.38	∞	∞	∞
Diamond 3x2x1.5 mm^3	1.1	0.7	∞	∞
Releasing process time (s) (Heating process)	FR4 substrate		Hardmetal substrate	
	COMSOL	Experiment	COMSOL	Experiment
Diamond 4x4x5 mm^3	0.006	N.A	N.A.	N.A.
Diamond 3x2x1.5 mm^3	0.006	0.5	N.A.	N.A

Table 9-2 Comparison of modelling and experimental results with diamond components

9.2 Force of the ice to solid contact

The relatively high grip force and contact stiffness are important advantages of this grip principle. The magnitude of the grip force is influenced by several parameters, including operation temperature, material combination and surface roughness. These parameters are experimentally studied and described in this section. In order to gain a clear view on the pertinence of these parameters, the mechanism of the grip force is primarily discussed before describing the experimental results.

9.2.1 Physical model of adhesion and force mechanism

The physical mechanisms that form the adhesion fall into three categories, including covalent or chemical bonding, dispersion or Lifshitz-Van der Waals forces, and direct electrostatic interactions, [Petrenko99-1]. The magnitude of these adhesion forces depends upon the combination of different materials (of gripper, part and liquid) and their properties. It is difficult to calculate the actual adhesive force solely on the basis of theoretical models.

The overall adhesion can be estimated using the free energy used for breaking the connection. The strength of the adhesion between two materials is defined on the basis of the work of adhesion, which is the free energy required to separate a boundary of unit area between the media [Petrenko99-1]:

$$W_A = \gamma_1 + \gamma_2 - \gamma_{12}, \tag{9-1}$$

with W_A as the work of adhesion, and γ_1, γ_2, γ_{12} as the surface free energy per unit area of the medium 1, medium 2, and the interface, respectively.

For liquid-solid contact, equation 9-1 can be rewritten as:

$$W_A = \gamma_{lv}(1+\cos\theta), \tag{9-2}$$

with $\gamma_{lv} = \gamma_1$ as the surface free energy per unit area of the liquid-vapor interface, and θ as the contact angle.

The bonding of H_2O molecules to a solid substrate is expected to be similar in water as in ice, because of the existence of the quasi-liquid layer. In this case, the W_A of ice-solid contact can also be determined by the contact angle of water to the same solid. In [Archer98], an equation similar to equation 9-2 is presented to describe the W_A of the ice-solid contact:

$$W_A = \gamma_{lv}(1+\cos\theta) + \pi_e, \tag{9-3}$$

with π_e as the increment in the solid-vapor free energy due to the adsorbed gases and liquids on the solid surface.

It should be noted that the correlation between adhesion force and the contact angle has been proven. However, this value may differ significantly from the actual measurement result. There are many reasons for this, including small cracks in the ice structure or the failure of the contact interface.

Chemical bonding or covalent bonding takes place in the contact interface of the gripping media and the component's surface. It is caused by the reaction of the gripping intermediate molecules and the molecules from the surface of the contact. Depending on the natural properties of the materials, the magnitude of the covalent bonding varies with different material combinations. For example, when the solid lattice more closely resembles the lattice of ice, it results in a higher bonding strength. As in [Petrenko99-1], for a perfect contact, the work of adhesion is larger than ~0.5 $J \cdot m^{-2}$. The force only acts over a distance in the order of 0.1 nm ~ 0.2 nm. According to [Petrenko99-2], it indicated that there is an insufficient understanding of the value of the covalent bonding.

In 1961, the Lifshitz-Van der Waals force was formulated by Dazyloshinskii, Lifshitz, and Pitaevskii. Later, Wilen reviewed their model and made calculations of the force values with respect to the ice to solid contact [Wilen95]. Most specifically, the quasi-liquid layer that exists in the contact interface has been taken into account. According to Wilen's estimation, the Lifshitz-Van der Waals force does not contribute a large portion to the overall adhesion. If by any means the gripper or the component is not fully discharged, direct electrostatic interaction will be present in the process. Depending on the contact condition, the portion of the electrostatic force may increase to 500 $mJ \cdot m^{-2}$ in the overall work of adhesion [Petrenko99-2].

The physical models describe the physical mechanism of adhesion, and the various adhesive force components. They permit the calculation of forces on the basis of idealized situations. In order to estimate the grip force in applications, another set of parameters, which are more obvious and controllable, need to be defined. This is discussed in the next section.

9.2.2 Influencing parameters to the adhesion

As mentioned earlier, the value of the actual adhesion force can differ largely from the theoretical estimation, due to a variety of influences. It is essential to identify the measurable and practical parameters that influence the adhesion force, and analyze their influence.

By investigating the force mechanism described in Section 9.2.1, the most important influential parameters with respect to the adhesion have been identified by this research:

- the combination of the material of the gripper tip, gripping intermediate and the component;
- the surface roughness of the target object; and
- the temperature required to pick up components.

The influence of the material combination has been previously mentioned. Materials differ in surface free energy and molecular structure, which result in different chemical bonding and electrostatic interaction. These contribute to the sum of the grip force. In applications, the material of the gripper tip is very readily changeable, due to the dependency on other physical parameters, (*e.g.* its thermal conductivity). This means that the same configuration of handling setup and process will result in different grip forces on target objects made from different materials.

The value of the grip force is influenced by the roughness of the contact surface. The correlation between surface roughness and adhesion bonding has been observed in [Archer98]. However, the quantitative analysis is difficult to undertake. The surface roughness represents the number of hills and valleys, and the difference between peaks and valleys that exist on the surface. A rougher surface indicates that there are more interlocks present in the contact interface. It also means that the actual contact surface is larger. This leads to a stronger connection between the ice and the substrate.

The grip force depends upon the temperature of the ice-object interface. In a certain range, when the break happens in the interface, a lower temperature results in a stronger gripping connection. The quasi-liquid layer has been used in an attempt to explain the change of adhesive force as a function of the temperature. In theory, the quasi-liquid layer has its maximum volume at the melting point. Investigations were previously conducted, and according to [Petrenko99-1], the shear strength of the ice-solid bonding reaches the maximum value at approximately –13 °C. This dependence can be shown in Figure 9-8. A similar temperature dependence trend can be expected for the tensile strength. According to the graph, it is suggested that the volume (thickness) of the quasi-liquid layer may have a great influence on the adhesion force.

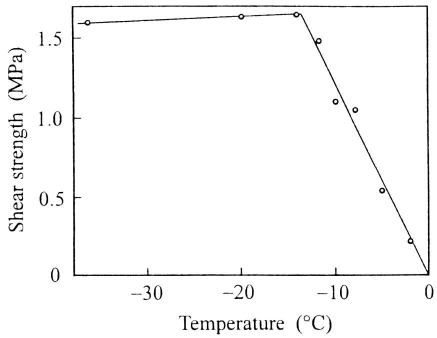


Figure 9-8 Temperature dependence of the shear strength of the adhesion of stainless steel to ice [Jellinek59] cited by [Petrenko99-1]

Experimental results are stated in the next section, which attempt to quantify and verify the influence of these analyzed parameters.

9.2.3 Grip force as related to the volume of gripping intermediate

The experiments of grip force are carried out on the force test bench which is described in Chapter 6. To test the force, sample objects are fixed to the measuring cantilever. The gripping contact is pulled until broken, while the gripping intermediate remains frozen. The maximum force is then recorded by the system. A fixed distance between the gripping tip and test sample is predefined in the experiments. Under such a configuration, the volume of the droplet in use determines the contact area. Tests are performed with sample parts made from polystyrene and aluminium.

The measuring results under 5 different droplet volumes, with sample material polystyrene, are shown in Figure 9-9, whereby the surface roughness *Ra* of the part is 0.9, and the gripping temperature is -30 °C. Multiple force measurement results, for the varying volumes of droplets, are plotted in the same graph.

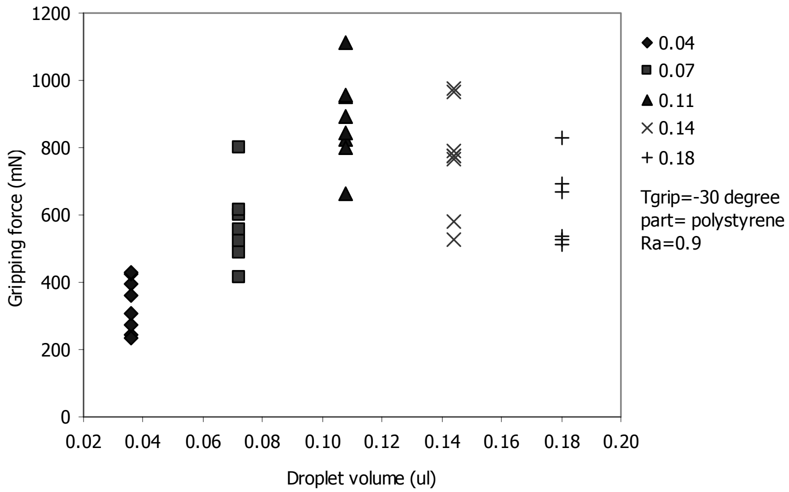


Figure 9-9 Droplet volume vs. grip force

The widespread data indicates that there is randomness in the ice forming process in the less controlled environment. It is noticeable that the grip force has a larger spreading area when more water is applied. In comparing the test of the grip cycle time, the data shows that the gripping process is less stable when an excessive amount of liquid is applied. Furthermore, an increase of the droplet volume over a suitable amount negatively influences the grip force.

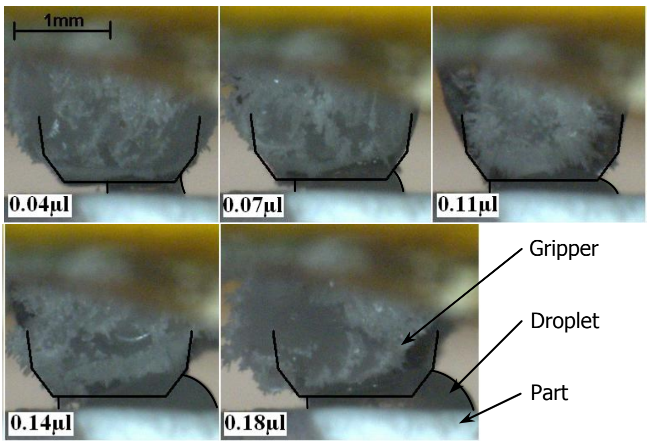


Figure 9-10 Microscopic view of the gripping contact with droplet volumes from 0.04 μl to 0.18 μl

Figure 9-10 shows the actual contact interface with different volumes of water. When the droplet volume increases from 0.04 μl to 0.1 μl, the additional amount of liquid contributes to expansion of the contact area. In testing, the grip force rose gradually. However, further increases of the volume of water reduce the curve of the grip force. When the volume of the droplet increases to 0.14 μl or 0.18 μl, the slit between the gripper and part cannot contain the entire droplet. The overflow of water increases the contact area with the target object, however, the interface area to the gripper remains steady, which causes no further increase of the grip force. The unevenly distributed droplet creates more stress and possible initial micro-cracks in the contact surface in the solidification process, which eventually reduces the grip force. In addition, the surface area of the droplet that is exposed in the open environment is increased, which causes a longer solidification time and more condensation. This aspect also contributes to the negative influence on the grip force.

The magnitude and value of the specific grip force provide more insight into the capability of the grip principle. By analyzing the measured microscope images taken in the gripping processes, the area of the gripping contact can be estimated. The grip force presented in Figure 9-9 is then averaged and translated into the specific grip force. The results are shown in Figure 9-11, where both the specific grip forces and the estimated contacted areas are plotted with respect to the droplet volumes.

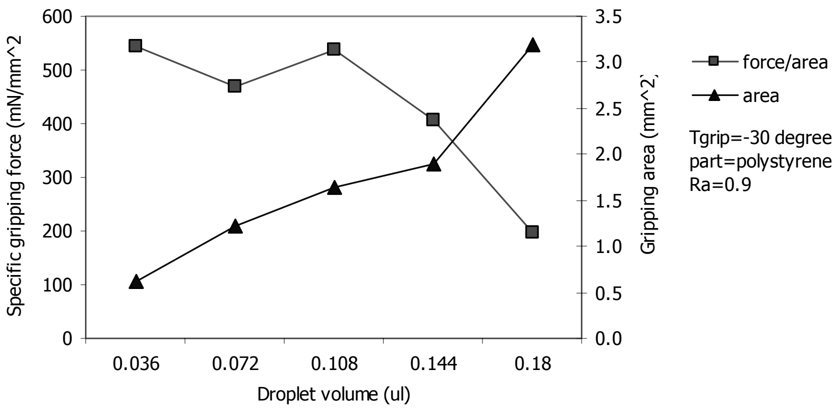


Figure 9-11 Specific grip force as measured under different droplet volumes

The value of the specific grip force shown in Figure 9-11 remains more constant at 500 mN/mm^2, when the droplet is less than 0.1 μl. As the excess volume of the gripping intermediate is used, a decrease of the specific grip force is measured. The reason for this effect has been illustrated in the general grip force measurements.

The same force measurement procedure is carried out with aluminium objects. The surface roughness of the sample is measured as $Ra = 0.8$. The tests were performed with a gripping temperature of -30 °C, with four different volumes. It is observed that the grip force and the specific grip force changes in a comparable trend, as measured in the polystyrene test. However, the grip force with the aluminium part is significantly larger than with that of the polystyrene part. Specific grip forces of up to 1.36 N/mm^2, and a characteristic value of 1 N/mm^2 were measured. The tests of the general grip force and the specific grip force are illustrated in Figure 9-12 and Figure 9-13, respectively.

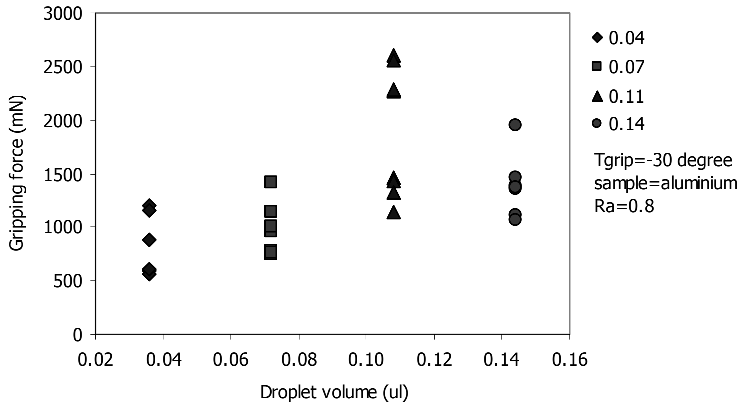


Figure 9-12 Grip force, as dependant upon a droplet volume with an aluminium part

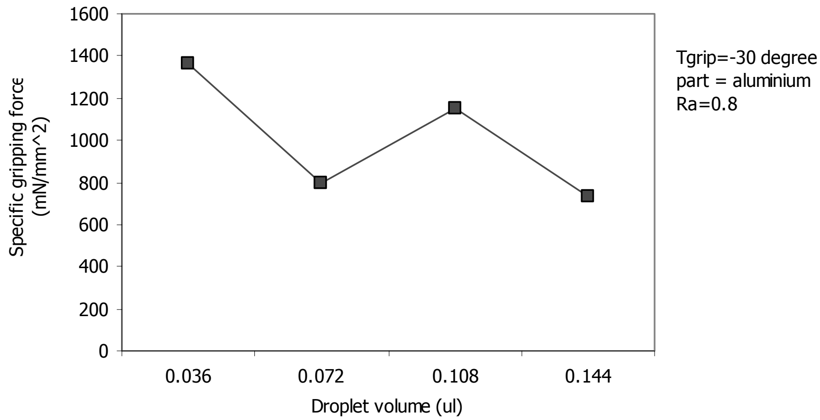


Figure 9-13 Specific grip force, as dependant upon a droplet volume with an aluminium part

9.2.4 Grip force as related to surface roughness

From a microscopic consideration, a rougher surface forms a larger contact surface with the gripping intermediate. Furthermore, there are more interlocking structures present when the intermediate is solidified. The enlarged contact area and the existence of interlocks contribute to the grip force. This influence is qualitatively studied.

In principle, two breaking modes can occur in the grip force test, including breakage in the intermediate, or breakage at the contact surfaces. Two contact surfaces exist in a gripping contact, between the gripper tip surface and the intermediate, and between the intermediate and the object surface. Any breakage in either contact surface means the termination of a gripping. The gripper is designed and implemented to have the breakage occur at the intermediate-to-object contact. Figure 9-14 shows two possible breakage modes of the contact. The breakage of the gripper side occurs incidentally in the test. In this set of experiments, only the break between the intermediate and the object surface is evaluated (as shown in the left image).

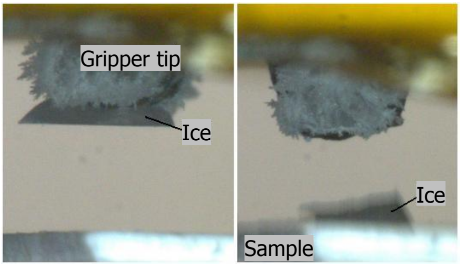


Figure 9-14 Two breakage modes of the gripping contact

The tests are conducted with glass and plastic parts. Each test consists of two different surface roughnesses. The droplet volume used in the tests is 0.1 µl, and the gripper temperature is -30 ˚C. The tests results are shown in Figure 9-15.

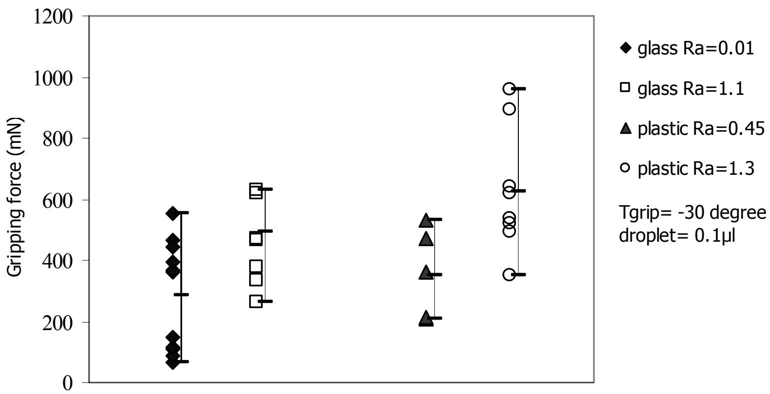


Figure 9-15 The relation of surface roughness and grip force

As expected by the analysis in Section 9.2.2, higher grip forces are measured on rougher contact surfaces for both glass and plastic parts. For the plastic object specifically, the grip force increases considerably when the surface roughness is higher. On average, a grip force of 350 mN is measured for plastic parts with *Ra* = 0.45. The value increases to 630 mN when a rougher surface is applied. It is worth noting that very high grip forces, some measured at over 800 mN, are recorded multiple times in the experiments. The results confirm the influence of the surface roughness on the magnitude of the grip force and specific grip force.

9.2.5 The relationship of the object material to the grip force

The material compatibility of the grip principle is one of the decisive factors of its application field. This issue is experimentally investigated by testing several major identical engineering materials. The semi-quantitative results received in this study provide a guideline for the grip principle implementation.

The testing environment as mentioned above is employed, wherein the experimental conditions consist of a gripping temperature of -30 °C, and a gripping intermediate of 0.1 μl of water. Five materials are brought into the test, and the results are summarised in Figure 9-16.

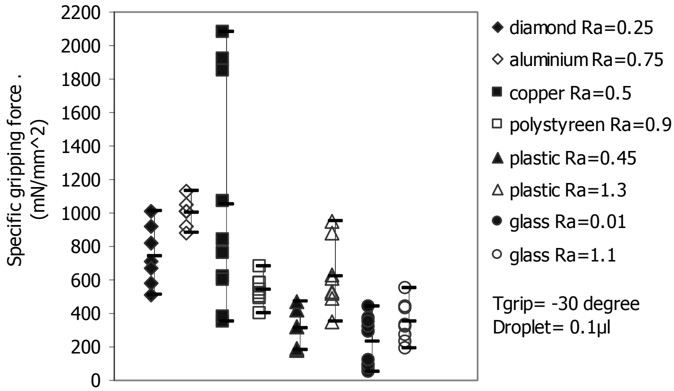


Figure 9-16 Test of gripper forces with different materials

The grip force data of the diamond and copper have a relatively wider spread compared to that of other materials. This is due to their high thermal conductivity. As a result of the heat flow, a part of the measuring cantilever that holds the diamond or copper samples is continuously cooled throughout the experimental process. However, the same solidification time is applied in all the experiments before the force measurement is taken. This testing configuration slightly changes the initial temperature of the experiment target. As a result, the measurements are taken under different temperatures and slightly different connection strengths. The results of the experiments from one side indicate that the substrate design for proper thermal behaviour is important for the actual gripping implementation.

The investigation results indicate that grip forces for the metal samples are significantly higher than for the other samples. The average specific grip forces for both aluminium and copper metal objects are above 1 N/mm^2. On average, a specific grip force of 0.8 N/mm^2 is measured for the industrial diamond parts. With non-metal samples, measurements show specific grip forces ranging from 0.3 N/mm^2 to 0.6 N/mm^2. [Warmer07].

In addition to evaluating the average results presented in Figure 9-16, it should be noted that the range of the specific grip forces observed with copper is scientifically interesting. A specific grip force of approximately 2 N/mm^2 is repeatedly measured. Although the value in this range failed to be consistent, it nevertheless indicates that the specific grip force is potentially even higher than what the literature suggested (1 N/mm^2) from [Kochan97].

9.3 Conclusions

Experiments of grip cycle times and grip forces are performed with the gripper prototypes, with demineralised water as the gripping intermediate. For a single operation, a grip cycle time of under 0.5 seconds is measured with plastic objects. For the continuous handling of plastic objects, the cycle time is achievable within 0.8 seconds. Highly thermally conductive objects, (*e.g.* diamond object) can also be handled with this grip principle. A continuous handling of diamond parts can be performed with a cycle time of less than 1.2 seconds, with a reliability of less than one failure out of 17 sequential handlings.

To ensure a reliable gripping operation, a certain low gripping temperature must be guaranteed. Meanwhile, the gripping temperature is the most important influential parameter with respect to the grip cycle time, and a lower gripping temperature results in a shorter gripping cycle. In addition to that, the grip cycle time is also sensitive to the geometrical configuration of the gripping intermediate. Two criteria help to optimize the gripping cycle. Firstly, the intermediate needs to spread uniformly on both the contact surfaces of the gripper tip and the target object. Secondly, it should be formed as a thin layer. A thinner layer and a larger contact area on the interface provide better performance, and thus, a shorter grip cycle time.

In using the low gripping temperature as an evaluation condition, the material combination is the predominant parameter on the grip force. A specific grip force above 1 N/mm^2 is achieved with metallic objects, while for non-metallic materials, this value decreases to 0.6 N/mm^2. Increasing the surface roughness of the gripping contact positively influences the specific grip force, due to the fact that the actual contact area increases by adding the roughness. The force value can be optimized by choosing a proper volume of the gripping intermediate in use. The result indicates that the force is sensitive to the solidification process and the geometrical configuration of the gripping intermediate. When the intermediate does not fill the gap between the gripper and the object entirely, the grip force is less, because the cooling surface is not fully employed. As an extra amount of intermediate is applied, the solidification process is negatively influenced due to the deformity of the intermediate layer.

10 General conclusions and recommendations

In recent years, micro-gripping has received an increasing number of academic efforts to fulfil assembly processes of micro-systems. An increasing number of components built in small-dimensions, having complicated geometries and large material diversities must be handled and assembled. The nature of micro-gripping is far beyond the handling of 2D components in 2D assembly processes as conventionally seen in micro-electronics manufacturing. A clear demand exists to bridge the gap between the rapid revolution of micro-systems and the limited assembly technology in manufacturing. Micro-gripping, the key issue of the entire assembly process chain must be strengthened with a better systematic understanding and further technological development. This issue has been the focus of this research project and the development of this topic is described throughout the thesis.

In this chapter, the research findings are concluded with respect to the defined research goals. For the reason that this research is strongly linked with industrial applications, the research findings are summarized individually from the knowledge, technology aspects, and from application aspects. The recommendations for future research direction are stated at the end.

10.1 Research findings

The research of micro-gripping technology has been approached two-fold in this thesis. As identified in Chapter 3, two primary barriers for micro-gripping technology to be implemented in applications are (1) primarily insufficient development of grip principles that are applicable, and (2), insufficient knowledge of proper implementation. Two research goals are thus defined in Chapter3.

Classification and (semi-)quantitative comparison of a variety of micro-grip principles. A framework for micro-gripping technology is defined and developed in this research. By using the framework, the process windows of various micro-grip principles are clarified. The research contributes to a systematic understanding of micro-gripping methods, and lays a knowledge foundation for process planning of micro-assembly.

Development of micro-gripping technology with respect to industrial applications. Special research efforts were devoted to the technological development of a specific grip principle based on the liquid solidification principle. The research contributes to a better understanding of the grip method on both the principle and implementation levels.

Further knowledge of the grip principle regarding industrial application is garnered. The grip cycle time, as one of the most important issues of the principle, is evidently shortened in comparison to the state of the art research.

With respect to the first research goal

By closely examining the operational processes and working principles of multiple micro-gripping methods and gripper designs, two fundamental definitions, namely, grip principle and actuation principle, are proposed in order to clarify the understanding of gripping methods. With the definition of grip principle, gripping methods are categorized according to their physical principles. This process enables the further classification research to be properly conducted. In total, 11 grip principles are identified and elaborately reviewed in Chapter 4.

For first time in the field, a framework of the micro-gripping technology is raised in this research, which lays a foundation for being able to compare gripping technologies and evaluate grippers in various aspects. The framework of the micro-gripping technology, as described in Chapter 5, is established in an effort to relate the micro-product with assembly technology. Critical issues from 3 categories are examined, including part-to-part parameters, part-to-equipment parameters, and production economical parameters. Criteria are defined under the origins of the technical parameters and economical parameters, which sufficiently cover the important aspects. Eventually, the framework is established upon 7 defined criteria, which are as follows: Specific grip force; Minimum number of contact points; Grip stiffness and retainability; Damage causes; Accuracy performance; Flexibility; and Grip cycle time.

A more detailed view of each grip principle performance is presented in the Process Data Sheet, and can be found in Chapter 5. It allows one to compare and select a grip principle on the basis of product and production features. As outlined in Chapter 4, the review of the grip principles is used as the information base.

From the knowledge and technology aspects, the achieved framework contributes to the systematic understanding of micro-grip principles and methods. It structuralizes the important issues that need to be tackled in research with respect to micro-gripping technology. The framework enables evaluation of different gripping methods with comparable criteria, and provides a better scheme for the presentation and selection of the gripping technology. The framework lays the foundation for the process planning for micro-assembly.

From the application aspects, the achieved framework serves as an easily accessible knowledge base for the micro-gripping technologies. It offers knowledge support with respect to micro-gripping from the conceptual level to the implementation level. The framework can be used as a guideline for selection of micro-gripping methods, and for assisting product and production development.

With respect to the second research goal

An alternative grip principle, liquid solidification gripping is studied for its promising features. Specifically, these are its high grip force, and high flexibility with respect to part materials and geometries. Research is performed in steps to maximize the capability of the gripping method and develop it towards industrial applications. In principle, the grip principle can be implemented with different concepts and gripping intermediates. However, it can be concluded on the basis of this research, as stated in Chapter 6, that one of the most promising strategies is to solidify water by freezing for the gripping action, and to melt the ice by heating for the releasing action.

With a well-developed working strategy realized in this research, the grip cycle time is evidently shortened in comparison to the state of the art research. For a single operation, a grip cycle time of less than 0.5 seconds is achieved in handling plastic components. For a continuous operation with diamond components, a grip cycle time of less than 1.2 seconds was observed. The working strategy, thermal design and the temperature control of the gripper are critical in achieving short grip cycle time. It is found that by maintaining the gripper at a consistently low temperature, the gripping time can be dramatically reduced.

Grip forces, in addition to specific grip forces, are for the first time experimentally investigated with a broad range of material parameters. The research concludes that the most influential parameters with respect to the grip force are the object material, gripping temperature and surface roughness. The influences are experimentally evaluated in this research. In general measure, a specific grip force of approximately 0.5 N/mm^2 was recorded for non-metallic parts and above 1 N/mm^2 for metallic parts. The grip principle showed high flexibility with respect to material and part geometry. Diverse, open structured components, with a very low contact area to footprint ratio, were successfully handled.

From the knowledge and technology aspects, the research into liquid solidification gripping identified the determinant parameters for the grip cycle time and grip force. The gripping strategy and gripper designs are raised on the basis of analytical and finite element analysis, which effectively improved the grip cycle time. With respect to the thermal process of the gripping, the finite element model provides a tool for understanding the process capability of this grip principle and guidance for gripping system development. The framework approach is reflected as the research methodology in the investigation of this grip principle.

From the application aspects, a reasonable grip cycle time is achieved for industrial implementation. Gripping flexibility with respect to part material and geometry are experimentally proved. Relatively high specific grip forces are measured with different materials. The influential parameters are concluded for the interest of the applications. The industrial applicability of this grip principle is investigated and demonstrated with a fully functional gripping system, which evidently bridges the principle research and industrial implementation of this micro-gripping technology.

10.2 Recommendations

With respect to the framework, further work is required to evaluate the grip principles by more quantifiable means. These efforts can further support the selection of grip principles, and further increase the usability of the framework. In contrast, the framework indicates that certain grip principles are less developed than others. Further academic effort will certainly expand the portfolio of the gripping technology.

The presentation and application method of the framework is worthwhile to further develop. By transferring the framework into software based applications, enhancements can be made to its application powers in order to broaden the benefits derived from it. Meanwhile, the framework approach can be further extended to cover the field of micro-assembly including other processes [Tietje07].

As proposed in Chapter 6, the liquid solidification strategy with UV light and thermosetting polymers is not thoroughly researched in this work. However, it is certainly a promising gripping concept. Furthermore, the grip cycle time has the possibility of being shortened by selecting or developing a proper gripping intermediate.

With regard to liquid solidification gripping with water as the gripping intermediate, further effort is necessary in order to determine the influential parameters for cycle time and grip force in detail. In the meantime, the gripping process can be more accurately controlled. The ultimate goal is to miniaturize the gripper body while maintaining the system performance in order to fit into broader application environments. Electrolysis is investigated in this research as a releasing principle, and has been proved functional. The interesting aspect of this principle is that it introduces very limited thermal influence to the gripping system, which can potentially improve the grip cycle time. Further development of this principle and integration of the principle into a liquid solidification gripping system could prove an interesting research topic.

In order to push the liquid solidification grip principle steps closer to industrial implementation, efforts are needed to develop more accurate control of the freezing and heating processes. In addition to this, efforts need to be made in stabilizing the gripping performance and improving the gripping reliability. Designs should be optimized with respect to the heating methods, thermal insulation, *etc*. More comprehensive sensing and control systems need to be considered for further development.

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