Attachment methods for Somaloy® components in mechanical constructions

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MASTER'S THESIS

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Abstract

Höganäs AB is asking for a way to attach *Somaloy*® components onto aluminum in electric motors. Gluing, Crimping and Clamping are the attachment methods that are investigated.

For the Gluing part, tensile tests are made at different temperatures. The tests are performed with six different adhesive combinations on aluminum and two separate *Somaloy*® materials. The adhesive's ability to attach onto the different sides of the *Somaloy*® component is also investigated.

The Crimping part is performed with an aluminum housing and a *Somaloy*® component. The housing is heated until expansion and the *Somaloy*® component is placed inside. When the objects are cooled down, the component is pressed out.

The Clamping part is only performed as calculations.

The results show that it is possible to attach *Somaloy*® components with the use of different adhesives, such as the epoxy, *Permabond ES550*. The tested adhesives are more willing to attach to the punch side of the component. Crimping can be used, but it should be noted that the method has been tested only at room temperature. Clamping is also an alternative for attaching the components; however, the design of the component would have to be remade to obtain a wider clamping edge. Moreover, only calculations and no testing were performed on the clamping method.

Keywords: Somaloy, Soft Magnetic Composites, SMC, attachment methods, metal powder, adhesive, gluing, crimping, clamping, Höganäs.

Sammanfattning

Höganäs AB eftersöker ett sätt att fästa *Somaloy*®-komponenter mot aluminium, inuti elmotorer. Infästningsmetoderna Limning, Krympning och Fastklämning undersöks.

För Limningen görs dragtester i olika temperaturer. Testerna utförs med sex olika limkombinationer, utförda på aluminium och två separata *Somaloy*®-material. Limmens förmåga att fästa mot de olika sidorna av komponenten undersöks också.

Krympningen utförs med hjälp av ett aluminium-hus och en *Somaloy*®-komponent. Huset värms upp till dess att det expanderar och *Somaloy*®-komponenten placeras inuti. När objekten har svalnat pressas komponenten ut.

Fastklämnings-delen undersöks endast med beräkningar.

Resultaten visar att det är möjligt att fästa in *Somaloy*®-komponenter med hjälp av olika lim, till exempel med epoxin *Permabond ES550*. De undersökta limmerna tenderar att fästa bättre på punch-sidan av komponenten. Krympning kan användas, med det bör noteras att alla krymptester är utförda i rumstemperatur. Fastklämning är också ett alternativ för att fästa komponenterna men för att lyckas med det måste komponenternas design göras om för att erhålla en bredare greppkant. Dessutom gjordes inga klämtester, utan enbart beräkningar.

Nyckelord: Somaloy, SMC, infästningsmetoder, metallpulver, lim, limning, krympning, fastklämning, Höganäs

Acknowledgments

The projects has been carried out at *Höganäs AB* in Höganäs, Sweden, from February to July in 2018, in collaboration with the Division of Material Engineering at LTH, Lund University.

I spent almost half a year at the office in Höganäs. Not only did I learn about SMC and adhesives, but how to interact with people, how to behave at a work place and how to move on from mistakes. I believe that my time at *Höganäs* will be a good foundation for me and my work in the future. Therefore, I would like to thank the office, *Magalie Darnis, Jamie Washington* and *Steven Jordan*, for providing this special time.

A special thanks, is sent to my supervisor *Hans Johansson Dahlskog,* for the support and help that I have been given throughout the project, but also for the inspiring discussions, guidance and wise words. The same goes to *Bo-Göran Andersson,* who constantly provided me with information and necessities.

I would like to thank *Michael Andersson*, *Per Helgesson*, *Jeronimo Lacno, Kim Holgersson*, *Johan Wahlund* and *Siv Olsson*, who helped me with calculations, taught me the equipment, provided me with materials, supported me, and came up with solutions when I messed up.

Of course, there are many more that made my time at *Höganäs* memorable, and I would like to thank you all for that.

Last, but not least, I would like to thank my supervisor at LTH, *Hossein Sina*, and my examiner, *Srinivasan Iyengar*, not only for the given support but also for believing in me and giving me the opportunity to fulfil this project.

Höganäs, June 2018

Cecilia Andersson

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List of acronyms and abbreviations

SMC	Soft magnetic composites
SURF	Substrate surface coating fracture

1 Introduction

This section is an introduction to the question at issue.

1.1 The Thesis

The thesis is made in cooperation with *Höganäs AB* as a part of their research and development in soft magnetic composite components.

1.2 Motive

A change in the car industry is making *Höganäs* uncertain about the future of their iron powder. More customers are changing from combustion engines to electric motors, which decreases the need for sinter pressed components, made from iron powder. *Höganäs* believes that this is just the beginning of the change [1].

The challenge is now for *Höganäs* as to find another potential use for their iron powder, possibly by making a new, more efficient, electric motor based out of their own materials.

In this work, the possibility of attaching two parts, the rotor and the stator, in the electric motor using methods such as gluing and crimping will be investigated.

The results will be used to give customers suggestions on how to construct the new engine. Moreover, to demonstrate that it is possible to make an efficient electric motor out of iron powder.

1.3 Background

Höganäs AB is a worldwide provider of iron powder. The iron powder is mainly used in combustion engines, now, *Höganäs* wants to show costumers that it is possible to create an electric motor with their material, *Somaloy*®. To do this they have to create a way to attach the parts, made out of *Somaloy*®, inside the motor.

The thesis will look into attachment methods such as gluing, crimping and clamping. For the gluing part, the project will test a varied amount of adhesives on the surface of *Somaloy*® and aluminum. The adhesives will be thoroughly controlled to surely fit the tight frame of regulations. To test the adhesives tensile tests will be made.

The project will also do a small series of tests to check if there is a difference in attachment of the adhesive between the die- and the punch side. This part of the project will be fairly based on a previous master thesis written by *Eddie Hedin* [2].

To test the method crimping, an aluminum housing will be heated up until it expands, placed around a *Somaloy*® component and then cooled down. The component will then be pressed out of the housing to see if the method could work as a valid attachment method.

The clamping part of the project will just be based out of calculations.

1.3.1 ***Höganäs AB***

Höganäs AB is a company with worldwide production of iron powder and headquarters located in Höganäs, Sweden. The main focus is producing iron powder for sinter pressed components for the car- and metal industry. However, as the car industry is changing their research and development department is trying to find another way of transforming the iron powder into new, useful components to fit new markets.

Höganäs believes that more customers, in the car industry, want to change their production lines from combustion engines made out of metal powder to electric motors. The question is for *Höganäs* to find a way to apply the iron powder on the new markets.

1.3.2 **Metal powder**

Höganäs’ metal powder is mixed into different combinations to fit the customer’s needs. According to *Höganäs* they produce and sell more than 1500 types of products thanks to the varied mixes [3]. The powder could be used for brazing, inductors and power cores, sintered components such as gears, thermal surfacing, 3D printing or as soft magnetic components.

1.3.3 **SMC**

A special part in *Höganäs*' production line is the soft magnetic composites, the SMC. *Höganäs'* SMC material, named *Somaloy*®, is used in cars such as the *Koeningsegg* to make the most powerful electrical motor set-up in history [4]. In the SMC every powder particle is covered with an insulating film making the component relatively resistant to Eddy Currents [2,5]. See Figure 1.

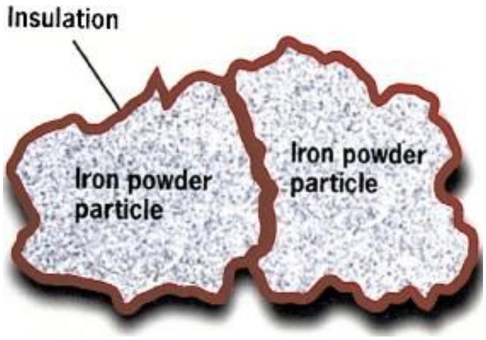


Figure 1: SMC powder particles covered with an insulating film [5].

If the particle is small, the Eddy Current grows small and with a high frequency voltage, the current changes direction frequently making it insignificant [6].

1.3.4 **Pressing**

Most of the components, made from the metal powder, are manufactured through pressing. The powder is pressed in a mold that is shaped according to the customers needs. Some of the components are pressed during heat and some are not. Some are also heat treated afterwards in different processes. The pressed component can have a complex geometry and is therefore an important piece in the industry.

1.3.5 **Die- and punch side**

It is shown that adhesives may attach with varied results depending on the side of the component [2]. The adhesive may work better if applied to the so called punch side of the component, se Figure 2. The reason is that the die side of the component will slide against the die during the compression process, which will shut the pores and make the surface more flat. Compared to the punch side, which will have open pores and a more rough surface.

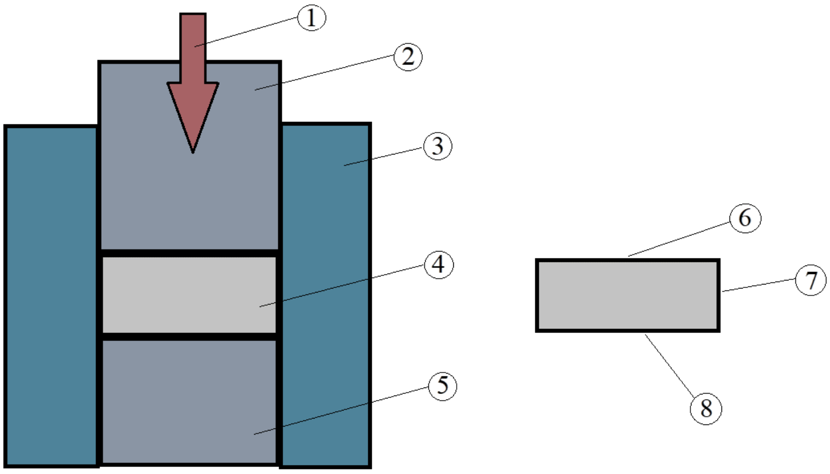


Figure 2: Showing a powder press and a pressed component.
1: Pressure, 2: Upper punch, 3: Die, 4: SMC component, 5: Lower Punch, 6: Upper Punch Side
7: Die side, 8: Lower Punch Side

1.4 Attachment methods

To attach the rotor and the stator, varied methods were discussed. *Höganäs* wanted to find attachment methods including as few process steps as possible. It was decided that Gluing and Crimping would represent the most probable methods at the moment, due to the current design of the motor, and that it would be interesting to know the size of an edge that was needed to make Clamping work.

1.4.1 **Gluing**

With the use of an adhesive, the components could be glued in place. Gluing is used in a large scale in companies around the world. Some companies have most recently discovered the techniques and benefits of gluing while other have used it for the past century. Today it is frequently used in the car industry as a way to attach engine components and bodywork [7].

The technique is simple: an adhesive is applied between the two surfaces that should be joined. When the adhesive have cured it makes a bond. The cure process can vary depending on the types of adhesive, a common way is to cure the joint in an oven in elevated temperature.

The joint will have a height, preferably 0.05-0.1mm, making the construction depend on tolerances [8]. It may be beneficial to put an even weight on the joints to ensure that the pressure is constant during cure [9].

Before the method is used a major safety analysis should be made. Some adhesives contain particles and substances that can cause serious damage to humans and wildlife [7,10].

1.4.2 **Crimping**

The components could be attached to the construction using crimping, which makes an almost unbreakable bond. At first the component is too big to fit in its housing. But then, the housing is heated up until it expands enough for the component to fit. The component is placed in position and the two will cool down and crimp together. Another way is to cool the component itself, which will make it shrink. In some extreme cases, both of the methods are used [11].

The method requires a heating or cooling process and precision during placement of the inner component. Apart from that, the method is relatively cheap and contains few steps. However, if the component is able to slide through the housing during heating it might slide back out if the object is exposed to heat later on during run.

1.4.3 Clamping

If a wider edge was applied to the stator, it could be used as an attachment. A step on an outer house could hold on to the edge and create a secure fastening, see Figure 3.

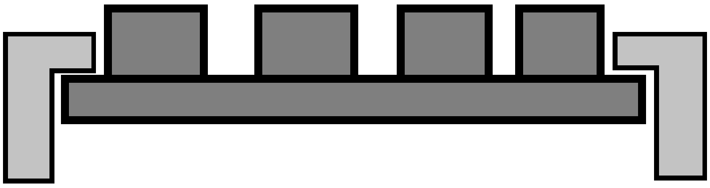


Figure 3: Schematic figure of a stator attached with clamping on the sides.

2 Method

In this chapter the literature study, performed methods, tests and calculations will be described.

2.1 Literature Study

As a basis for the literature study, another master thesis was used, written by *Eddie Hedin* at *Mechanical engineering, Lth* [2].

Some of the gluing parts of the project were based out of previous projects at *Höganäs,* where similar adhesives and materials were used [1].

Höganäs have a varied amount of contacts working with adhesives. Some of these were contacted during the project to get a broader understanding of the products and their area of use.

For both the SMC and the different attachment methods inventions were made both in literature and within the company itself.

In this chapter the different information sources will be discusses.

2.1.1 **Previous report on adhesives and *Somaloy®***

In a previous master thesis, written by *Eddie Hedin, Mechanical engineering, LTH,* a similar project was preformed [2]. *Hedin*'s goal was to find out what adhesives that could work on *Somaloy*® in different temperatures and with varied surface treatments. The thesis focused on gluing *Somaloy*® to *Somaloy*® but the testing process included tensile tests.

Hedin found adhesives that worked on his materials both in room temperature and in elevated temperature. His research also showed the importance of surface treatment, which played a major part in this project. He could also detect some differences in attachment of the adhesives depending on what side of the component the adhesive was applied on. He called it *die- and punch side*. Moreover, he stated that the adhesives had stronger ability to attach on the punch side of the component. See chapter *Die- and Punch side*.

2.1.2 **Previous gluing projects**

Höganäs has used adhesives to attach parts in engines in previous projects. They built an electric bike where the engine was based out of their material Somaloy® and neodymium magnets such as the ones used in this project [1]. See Figure 4. There were not much material to have as a foundation for this thesis, but the projects were used as a guideline and motivator, knowing that someone had managed before.

From the projects a useful adhesive was found, this was brought into the thesis.

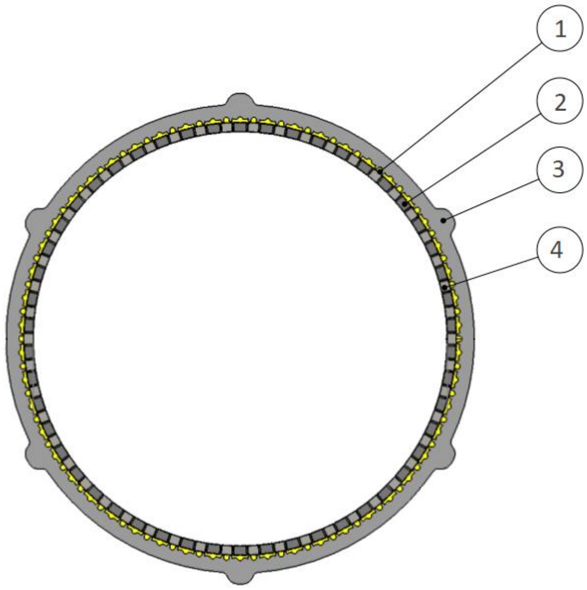


Figure 4: Previous engine (rotor) attached with glue.
1: Adhesive, 2: Pole Piece, 3: Housing, 4: Neodymium Magnet [1]

2.1.3 **Adhesives**

2.1.3.1 Adhesive Inputs

A major research for adhesives was performed. The goal was to find adhesives that fit the framework of the project. Adhesive resellers were contacted and asked to recommend two or three different adhesives that matched the projects specifications.

From *GA-Lindberg*, it was recommended to use products from *Permabond* and *Loctite* [12]. Some of the products was already in use at *Höganäs* and some of them had been used in the previous Master's Thesis [2]. However, the contact at *GA-Lindberg* did not take into account the safety aspect of the products that were recommended. Later on, it showed that one of the products did not match the safety requirements and had to be removed from the list of potential adhesives.

From *ABIC,* it was first recommended to use two different two-component epoxy adhesives with high shear strength. However, from discussions during a meeting with representative *Mats Jussila,* it was recommended to use a one-component epoxy instead [8]. This one matched the requirements in an other way than the two first ones. The new adhesive had an impressive shear strength, (up to 60 MPa) and a fitting shear- and Young's modules, according to *Jussila*.

Jussila meant that the shear- and Young's modules were important when heating and cooling the components. If the adhesive did not expand or contract like the aluminum and *Somaloy*® the adhesive would break. However, if an adhesive was more elastic it could behave like and follow the movements of the components, which would make a better bond.

There was a discussion whether one of the products, the accelerator *Loctite SF 7471*, was supposed to be applied directly on the gluing surface or afterwards from the outside of the component. *Loctite* was contacted and the producers answer was that the product should be applied directly to the surface and let dry and evaporate before getting in contact with the base product [13].

2.1.3.2 Requirements of the Adhesives

The adhesives had to fit a tight frame of requirements to fulfill the tests. However, even though some of the adhesives did not match all of the requirements, they were still taken into the tests, but evaluated at a later point.

The base requirements were:

- The adhesive should be safe to use according to *REACH* [14]
- The adhesive should be of one component
- The adhesive should have cure time around an hour
- The adhesive should take tensile stress above 20MPa
- The adhesive should take tensile stress in -30 degrees Celsius
- The adhesive should take tensile stress in room temperature
- The adhesive should take tensile stress in 125 degrees Celsius
- The adhesive should take tensile stress in 155 degrees Celsius
- The adhesive should work in production and industry
- The adhesives should work on flat surfaces of Somaloy and Aluminum

2.1.3.3 The Adhesives used in the test

Six different adhesives were tested, all strong on different parameters in the list of requirement.

2.1.3.3.1 Loctite 648

The base *Loctite 648* was found in a process used at another department at *Höganäs* where they use it to join inductors. The whole process of adding the adhesive was copied from their actual gluing process. The adhesive and the gluing process was also found in the previous master thesis where the results were outstanding, both in normal and elevated temperature [2].

The product is a single component anaerobic adhesive. It should have high temperature resistance properties and a shear strength around $26{,}5\ MPa$. The adhesive should cure for two hours in room temperature [15].

The adhesive is used together with a degreaser, *Loctite SE7063*, and an accelerator, *Loctite SF7471*.

The combination of *Loctite 648*, *Loctite SF* 7063 and *Loctite SF7471* will further on be noted as *L1*.

2.1.3.3.2 Permabond ES550

The base, Permabond ES550, was recommended from contacts at GA-Lindberg [12].

The product is a single component epoxy, which should have excellent adhesive strength, a shear strength between $17 - 31\ MPa$ when used on aluminum and high temperature resistance. The adhesive should cure for 60 minutes in 150 degrees Celsius [16].

Permabond ES550 will further on be noted as L2.

2.1.3.3.3 Permabond ES562

From previous projects at *Höganäs*, the base *Permabond ES562* was found as an interesting part. The product had been used to join neodymium magnets to an aluminum housing [1].

The product is a single component epoxy with high shear strength, $14 - 17\ MPa$ when attached to aluminum, and a tensile stress up to $40\ MPa$. The adhesive should cure for 60 minutes in 130 degrees Celsius [17].

Permabond ES562 will further on be noted as *L3*.

2.1.3.3.4 Araldite AV4600

The *Araldite AV4600* was a new addition to *Höganäs'* adhesive record. It was recommended from the contact at *ABIC* during a meeting [8].

The adhesive is a single component epoxy with a shear strength over $30\ MPa$ and heat resistance over 160 degrees Celsius. It should cure in 180 degrees for 30 minutes [18].

Araldite AV4600 will further on be noted *L4*.

2.1.3.3.5 Permabond 820

The base, *Permabond 820*, was found on *GA-Lindberg'*s webpage. The adhesive met the requirements and was of another kind than the rest, which made it interesting [19].

The adhesive is a cyanoacrylate with a shear strength at $19 - 23\ MPa$ and said to be suitable when high temperature resistance is required. It should cure for 24 hours in room temperature [20].

Permabond 820 will further on be noted *L5*.

2.1.3.3.6 Permabond HH131

The base, *Permabond HH131*, was found on *GA-Lindberg'*s webpage and then discussed with their contact [12].

It is a single component anaerobic sealant with a shear strength at $17\ MPa$. It is said to be suited for applications requiring high temperature resistance. The adhesive should cure for 24 hours in room temperature to reach full strength.

Since the adhesive is anaerobic, it cures in absence of oxygen, which means that it needs an accelerator, hence, the use of *Permabond A905*.

The combination of *Permabond HH131* and *Permabond A905* will further on be noted L6.

2.1.4 **Benefits with Soft magnetic components**

In an article, soft magnetic composites (SMC), was described as metal powder covered with an insulating film. This should make the material relatively resistant to Eddy Currents since the currents would not be able to wander through the material [5].

From discussions at *Höganäs*, with application specialist *Steven Jordan*, it was made clear that the Eddy currents grow smaller in the SMC because of the small particles, the powder particles. In a solid material, the currents may flow wherever they want, but in a powder component, the currents are locked into separate particles and will therefore stay small. *Jordan* states that the Eddy currents causes heat loss, which is proportional to the size of the currents, making the structure of metal powder beneficial in this situation [6].

Pressed components are beneficial due to the easy manufacturing and the complex geometries see *SMC in electromagnetic applications* [21].

2.1.5 SMC in electromagnetic applications

SMC components will be found in optimized electromagnetic designs that are taking advantage of the 3D isotropic nature. The components are suitable for electric motors designed for easy manufacturing and assembly, and for automated, high volume production. Use of SMC components will reduce the total application cost due to size reductions. There are no direct replacements for this kind of components.

The SMC components can be found in compact, high performing and cost-efficient axial flux motors from 100W to 200 kW. This is thanks to the electromagnetically and thermally isotropic material that allows flow of magnetic flux and heat in all three dimensions. Powder size and thickness can be tailored to suit several electromagnetic motor concepts, competing well against $0{,}5\ mm$ and $0{,}35\ mm$ electrical steel laminations [21].

2.2 The components

The SMC components are pressed and heat-treated at *Höganäs*. Unlike other pressed components, the SMC is not sintered but run through an oven to burn off binders at a lower temperature. See chapter *Heat Treatment.*

For this project a rotor and a stator is used. The rotor is made out of the material Somaloy 1P. It is flat on one side and has hollows on the other, where the magnets go. The stator is made out of Somaloy 5P. It is designed to hold copper bobbins therefore the teeth. See Figure 5 and Figure 6.

Figure 6: the Rotor in 1P material

Figure 6: the Stator in 5P material

In Figure 7, it can be seen where the attachment or joints would appear in the complete construction. The blue lines symbolize the adhesive joints.

For the tensile tests other products were used, which were easier to apply in the test equipment. See chapter *Tensile Test*. However, it was important to use components that were made from the exact same material as the real rotor and stator to get the correct material properties. See chapter *Test Components*.

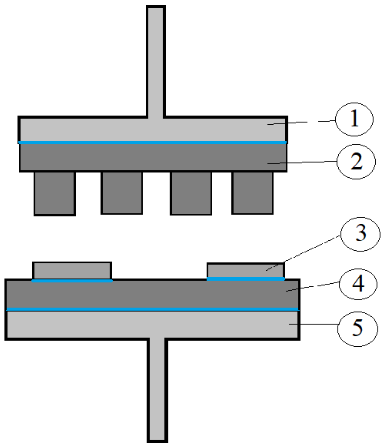


Figure 7: Showing the complete construction. 1: Aluminum, 2: Stator, 3: Magnet, 4: Rotor, 5: Aluminum.

2.2.1 **Test Components**

The goal was to find test components that were as similar to the real component as possible, in both material properties and size. The real components could not be used for the tensile tests due to incompatibility with the testing equipment.

The test component, for the tensile tests, was instead cylindrical pucks, made out of the same materials as the rotor and the stator. Both the diameter and the height of the pucks turned out to be 25 mm, due to limitations in the pressing tool. The pucks were pressed in *Höganäs*' own powder press.

However, the test components got a special surface due to the heat treatment; see Figure 8 and 9, and chapter *Heat Treatment*. There were differences between the top and bottom surfaces of the components. It was discussed whether they were representative surfaces or if the components had to be remade. It was decided that the top and bottom surfaces, and their differences, had to be taken into account while doing the tests, to make sure that it had no impact on the results, but no remake was made.

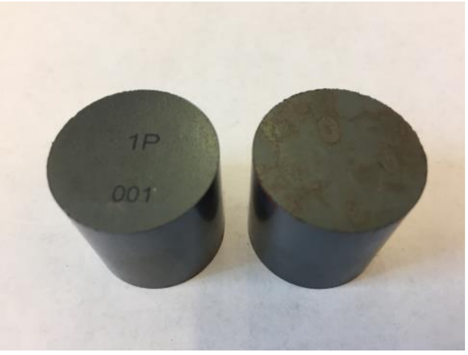


Figure 8. 1P Puck. Top and Bottom

Figure 9. 5P Puck. Top and Bottom

The components also had a small edge due to the pressing tool. Se figure 10. The real components, the rotor and the stator, did not have the same edge because of the way it was drawn. To make the test components representative the edge hade to be removed. Se chapter *surface treatment* and *edge removal*.

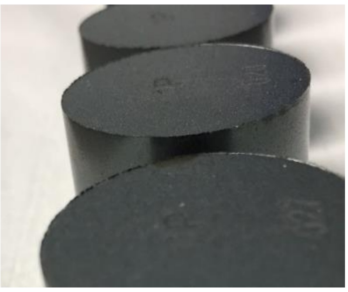


Figure 10: Edges on pucks

For the crimp test, the real stator was used. The bulk test was performed on six different stators, randomly collected from a series of 500. Se Figure 11. For the last test, test nr 7, an extra stator was used. This stator was also randomly taken from the same series but thought of later on in the process. The diameter of the last stator was measured with an caliper and was $d_7 = 64{,}99\ mm$.

The diameters of the six components were measured in *Kordinatmätmaskin Zeiss Duram ID:6656*. The measurements can be seen in Table 1. From the measurements, it was also shown that the stator components were not completely round, but somewhat oval. From the same table it can be seen how oval/round they were and Figure 12 shows a sketch of where the irregularity appears.

Figure 11: Stator components used in the crimp tests.

As seen in the picture, Figure 12, which shows the roundness of the stators, the blue line does not follow the perfect black line, but moves in an area of 20 um around it. The blue line represent the actual measurements of the stators shape and the black line is the expected value.

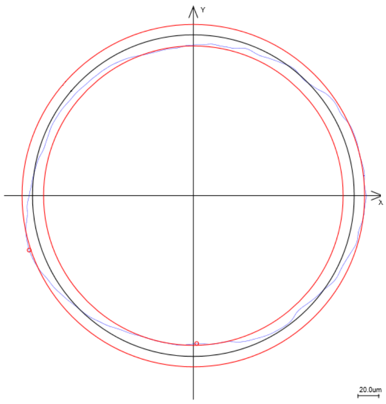


Figure 12. Roundness measured on stators.

Table 1: Showing the measured diameters (mm) and the roundness of the six test stators.

	1	2	3	4	5	6
Diameter	65,005	65,004	64,999	65,002	64,999	65,000
Roundness	0,020	0,021	0,022	0,025	0,026	0,023

For the die- and punch side tests, rectangular components of 1P and 5P materials were used, see Figure 13 and Figure 14.

Figure 13: TRS component in 1P material.

Figure 14: IE component in 5P material.

They were needed to be rectangular to provide a flat die side where the adhesive could be applied. The size of the components were decided due to limitations in the pressing tool. For the 1P material, the size was:

$l_1 = 30{,}21\ mm$

$h_1 = 12{,}23\ mm$

$w_1 = 12{,}11\ mm$

The contact area, with the aluminum cylinder during gluing, was calculated as a rectangle with the length of the diameter of the aluminum cylinder and the height of the component. Making the 1P die contact area:

$$h_1 * d = 305{,}75\ mm^2 \quad (2.1)$$

The punch contact area became a rectangle with the length of the diameter of the aluminum cylinder and the width of the component making the 1P punch contact area:

$$w_1 * d = 302{,}75\ mm^2 \quad (2.2)$$

Where d is the diameter of the circular aluminum puck.

For the 5P material, the size was:

$l_2 = 55{,}10\ mm$

$h_2 = 11{,}95\ mm$

$w_2 = 10{,}17\ mm$

Making the 5P die contact area:

$$h_2 * d = 298{,}75\ mm^2 \tag{2.3}$$

Making the 5P punch contact area:

$$w_2 * d = 254{,}25\ mm^2 \tag{2.4}$$

Where d was the diameter of the circular aluminum puck.

The surface of the components were not ground but the edges were removed as the ones for the GD pucks, they were also heat treated in the same way as the GD pucks, see chapter *Heat Treatment*.

2.2.2 Heat treatment

The heat treatment process is typically a two-step heat-treatment in order to release the lubricants from the component, obtain partial stress relief of the component after compaction and, finally, to gain additional strength. The temperature selected should be the highest possible to ensure high stress relief but without destroying the electrically insulating surface coating [22].

To get the special material qualities, the components had to be heat treated in the same ways as the real rotor and stator. For the 1P material this meant pressed without heat and then put in an oven. The oven temperature can be seen in Figure 15.

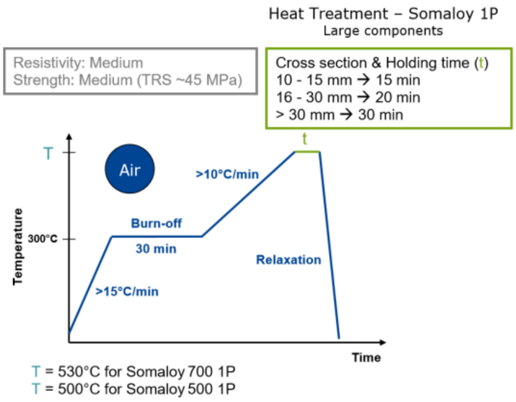


Figure 15: The recommended heat treatment for 1P components.

The 5P components were pressed during heat and then heat treated in an oven at a temperature that can be seen in Figure 16.

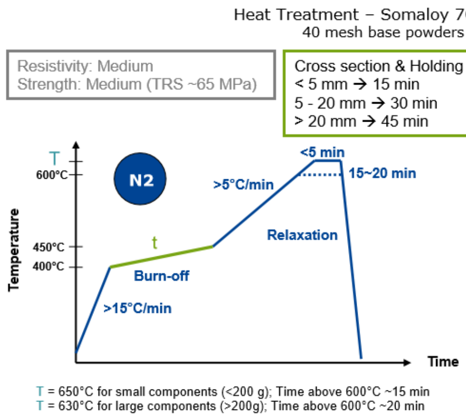


Figure 16: The recommended heat treatment for 5P components.

When the 5P component is heat treated, it gets a brown layer of waste material on top of its surface. *Hedin* states that this layer must be removed before adding the adhesive or the top layer of the component will come off during tension. He calls it substrate surface coating fracture [2]. To ensure that it was applicable on these components as well, the testing was made with different surface treatments, such as grinding. See chapter *Surface treatment*.

It was also to consider whether the parameters of the oven, during heat treatment, could be changed in some way to get a better surface. Maybe a change of parameters could change the top layer and for example decrease the need of grinding.

It was discussed whether the thickness of the test components had to do with the extreme surface structure. It was stated that the bottom surface should be the same regardless of the thickness of the component. Which meant that the adhesives ability to attach on this side should be representative for the real components [22].

2.2.3 **Created Fixtures**

To be able to perform the different tests, several fixtures had to be created.

2.2.3.1 Aluminum Cylinders

The purpose of the aluminum cylinders were to provide a gluing surface of aluminum and to be the fixture that would fit in the tensile test machine. The Cylinders were created with a big diameter, which was the exact same as the one of test components, $25\ mm$, and a smaller diameter to fit in the machine, $17\ mm$. To minimize the risk of introducing stresses, a radius was created from the bigger diameter to the smaller. See Figure 17. During the testing face, the aluminum cylinders were reused. When a tensile test was done, the cylinder was lathed and brought back in the process.

Figure 17: Aluminum cylinder.

2.2.3.2 Aluminum Gluing Fixture

To be able to center the glued pieces, during the gluing process, a gluing fixture had to be designed. The prototype for the gluing fixture was made out of wood. It had vertical, circular slopes where the glued objects should fit. See Figure 18.

For the real fixture the slopes where made as V-shapes which would give the objects the same possibilities to be centered but provide an easier manufacturing. There was also introduced an angle to the whole fixture, making the objects fixed in every dimension. See Figure 19. The fixture can be seen during use in Figure 20.

Figure 18: Wooden prototype.

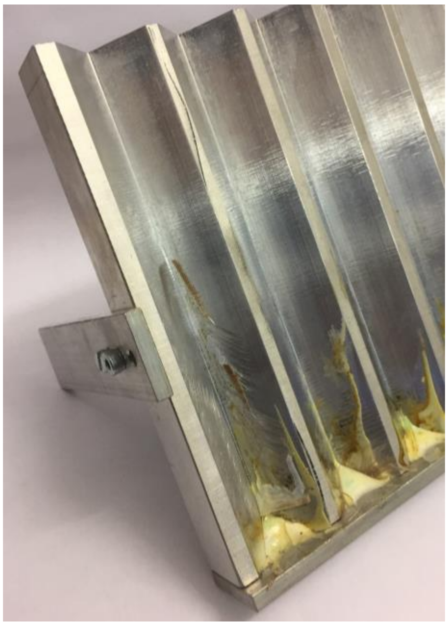


Figure 19: Aluminum Gluing Fixture.

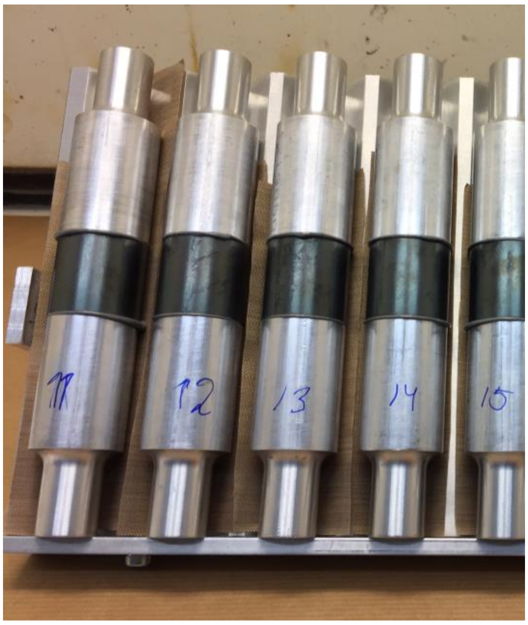


Figure 20: Glued objects standing in the Fixture.

2.2.3.3 Aluminum Crimp test Fixture

For the crimp tests, a housing had to be designed, see Figure 21and Figure 22.

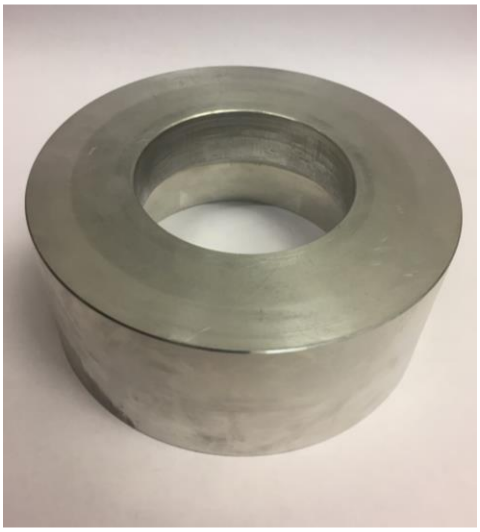


Figure 21: Crimp Test Fixture, top.

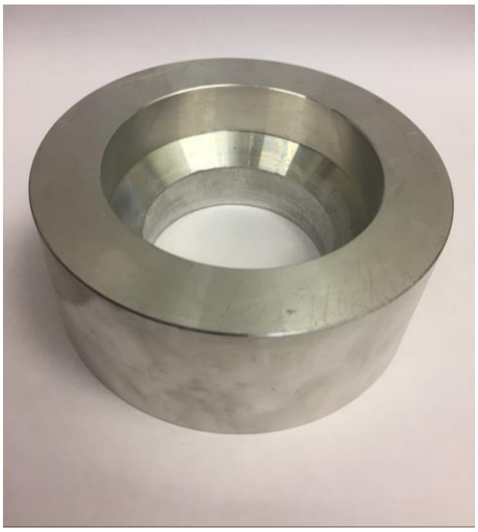


Figure 22: Crimp Test Fixture, bottom.

It was decided to have a hole where the stator should fit and to heat up the housing but to leave the stator in room temperature. The size of the hole, a, was calculated as follows, see Figure 23 for the different measurements.

$$p = \frac{\Delta d}{2(\frac{a}{E_{housing}}\left(\frac{a^2+b^2}{a^2-b^2}+v_{housing}\right)+\frac{d}{E_{stator}}\left(\frac{d^2+c^2}{d^2-c^2}-v_{stator}\right))} \tag{2.5}$$

$$p = \frac{F}{\pi\, 2d\, L\, \mu} \tag{2.6}$$

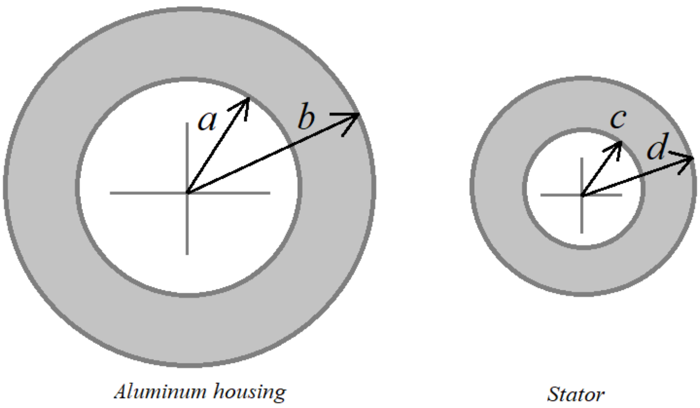


Figure 23: Measurements of the characteristic dimensions of the aluminum housing and stator.

Where p was the surface pressure on the stator component, and F the required force to withstand stresses caused by the magnets. Δd was the radial grip, the difference between a and d.

A normal grip is about 0,1-0,2% of the radius of the component [23]. Through searches and discussions, it was decided to have a grip with a safety factor of ten. The new grip was then: $\Delta d = 120\ \mu m$.

It was calculated to see if the aluminum housing were going to be able to expand enough to come around the stator component. The diameter of the housing after heating would be:

$$D_{new} = D * \alpha * \Delta T \tag{2.7}$$

Where D was the diameter when the housing was at room temperature, α was the coefficient of thermal expansion for aluminum and ΔT was the temperature difference, going from 20 degrees Celsius to 250. Since the new diameter was calculated to be more than $0{,}2\ mm$ bigger than the stator component, it was decided that it should be able to fit.

The outer diameter of the aluminum housing was decided from usual wall thicknesses from previous orders [1].

For the stator to be able to fall down in the measurement machine, the aluminum housing had to have a special design and big space under the stator. The space was created as a bigger diameter and a chamfer between the two diameters. A block, with screws was also designed to be able to hold the stator at different positions, see Figure 24.

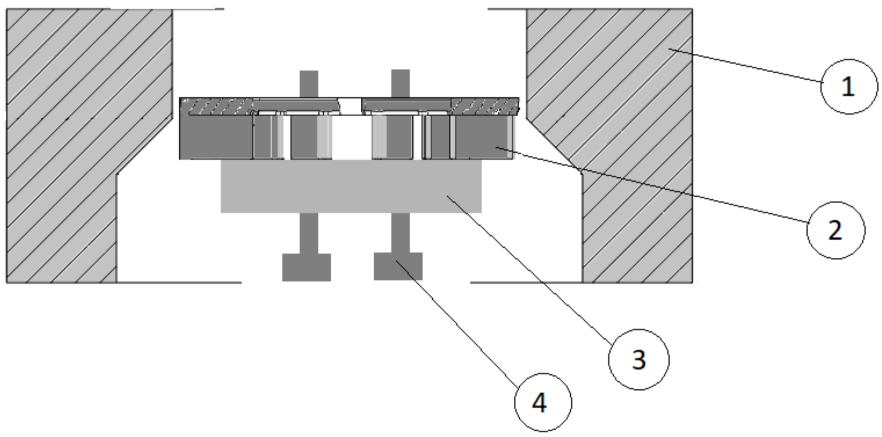


Figure 24: 1: Aluminum housing/crimp test fixture, 2: Stator, 3: Block, 4: Screws.

2.2.3.4 Plastic Cylinder

To be able to place the stator inside the aluminum housing a plastic cylinder was created. The cylinder had to hold the stator and let the screws, from the block, come up inside it, requiring some exact measurements. See Figure 25 and Figure 26. The cylinder was also a tool for pressing the stator out of the aluminum housing during the actual test.

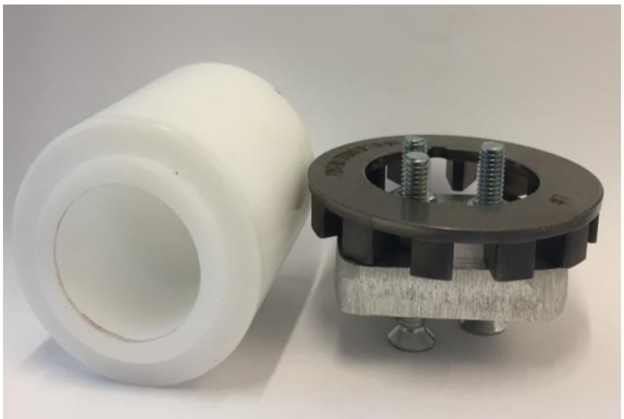


Figure 25: Plastic Cylinder, Stator and Brick with screws.

Figure 26: Cylinder arrangement.

When the first crimp test was made, it was clear that the cylinder used for pressing the stator out had to be bigger, or bending was introduced to the stator. A second cylinder was therefor made, with a bigger diameter to spread the force equally on the stator.

2.2.4 **Surface treatment**

2.2.4.1 Grinding

Through previous projects, it was made clear that the surface was going to play a major role. For the surface to be as perfect as possible, and to get a steady reference while testing, all of the adhesives were tested on a pre grinded surface as a first state.

The top layer of the component was removed by grinding. See Figure 27 and Figure 28. The grinding was made by hand, using a grinding machine and a 350 sand paper.

Figure 27. 1P components.
Left: Ground. Right: Original.

Figure 28. 5P components.
Left: Ground. Right: Original.

Figure 29. Aluminum cylinder surfaces.
Left: Ground cylinder. Right: Original cylinder.

The aluminum cylinders were also ground to ensure that all of the surfaces had the same pre conditions. See Figure 29. This was made for all the tests, even the variants where the SMC components had no surface treatment.

2.2.4.2 Edge Removal

The test components had a small edge of powder material all the way around the top and bottom, due to the pressing tool. See Figure 30. This hade to be removed to make the components representative. The removal was made on all of the components after the verification of the test method. See chapter *verification of test methods.*

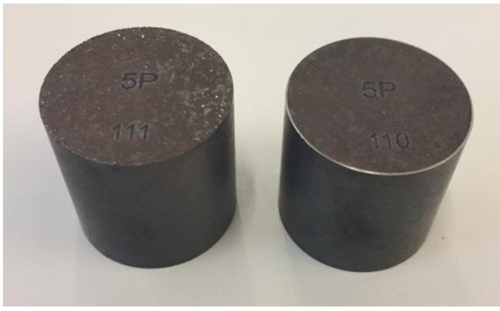


Figure 30. SMC components.
Left: Edge still on. Right: Edge removed.

The edge was removed by hand, using a grinding machine and a 320 sand paper to get similar results on every piece, see Figure 31 and Figure 32.

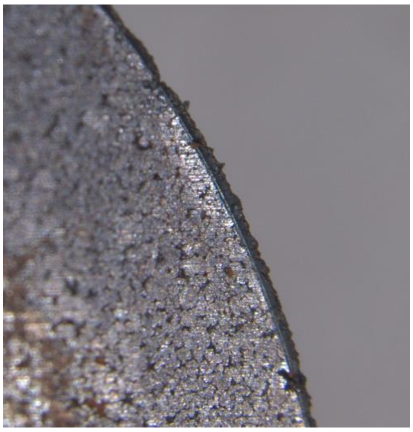


Figure 31: SMC edge. Edge still on.

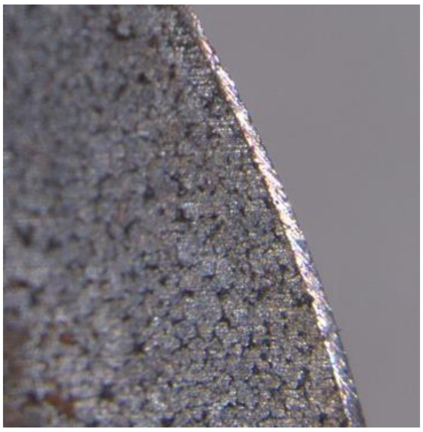


Figure 32: SMC edge. Edge removed.

2.2.4.3 Degreasing

One of the glue combinations included degreasing as a step in the process. However, there were no systematical degreasing preformed on the rest of the test components due to the objective of finding an attachment method with as few process steps as possible.

2.3 Test Methods

The tests were performed in *Höganäs'* test hall.

2.3.1 **Gluing**

The goal of the gluing was to find an adhesive that would join SMC and Aluminum in room temperature and in the temperatures fitting for an electrical motor. The gluing process should obtain as few process steps as possible and be relatively safe to use for the industry workers and the environment. The force provided by the magnets in the construction was $F = 270\ N$ which gave the tensile stress $\sigma = 0.13\ MPa$.

2.3.1.1 The making of the tensile tests

Ten aluminum cylinders were placed in the aluminum gluing fixture with the small diameter down. Ten SMC pucks, five of 1P and five of 5P were placed in front of the gluing fixture.

The gluing surfaces was then prepared with degrease, activator or base substrate, depending on the adhesive combination, and put together in the gluing fixture.

Ten new aluminum cylinders were placed in front of the gluing fixture and all of the new surfaces was prepared in the same was as above. The aluminum cylinders were then places on the pucks in the gluing fixture.

The objects were centered and let to cure, see Figure 33, ether in an oven at specific temperatures or in the fume cupboard in room temperature.

The objects where marked with a number and a special letter combination to sort out what material, surface treatment, test temperature and adhesive combination had been used.

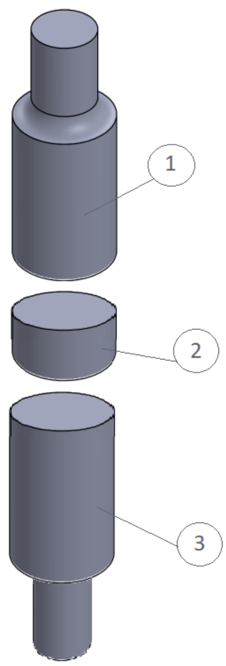


Figure 33: Gluing object 1: Aluminum, 2: SMC, 3: Aluminum

2.3.1.2 Verification of test method

To see if the tests were going to be reliable, a series of verifications tests were made. The tests started out with the ones that were thought to have the most perfect conditions. Meaning a grinded surface in room temperature and the most reliable and most used adhesive so far, *Loctite 648*.

Later on, the ruff surface was tested and it was found that the edge had to be removed and that it was critical to make sure that the adhesive filled the whole surface. When the edge was still on, some adhesives could not interact with the entire surface and would therefor brake at unpredictable stress levels. Some of the verification tests can be seen in Figure 34.

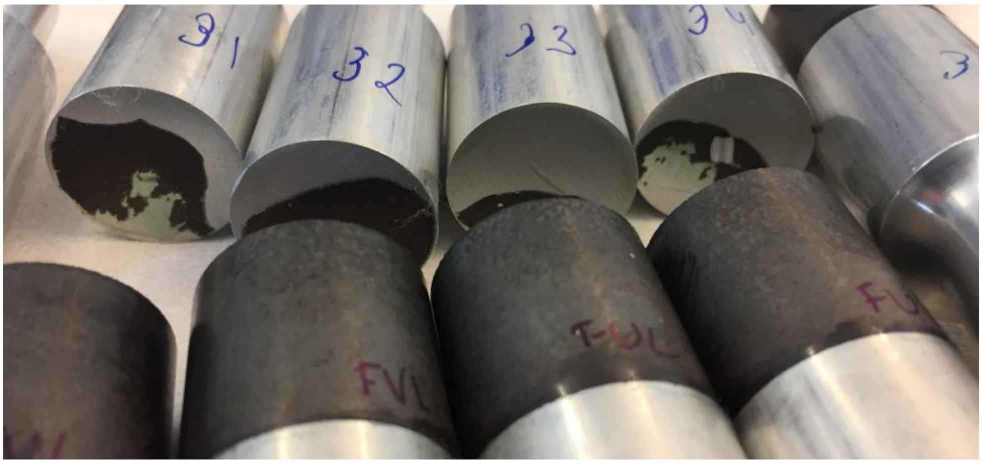


Figure 34: Verification tests. The adhesive was not able to interact with the entire surface due to an edge on the SMC component.

The verification also tested the difference in top and bottom surface by turning the component upside down. It did not matter for the test what surface was up, see *Results*.

2.3.1.3 Tensile tests

The tensile tests were all preformed in the *Amsler dragprovare*, ID: *4459*, at a speed of 100N/s. The machine settings were as follows:

- Small piston (lilla kolven): 1
- Measurement ring (mätring): 98kN
- Hole setting (hålinställning): I

The settings made it possible to measure up to $9800\ N$ at a 1 to 1 scale.

The objects were placed in the machine and tightened with as little power as possible. See Figure 35.

The objects were exposed to tensile stress until fracture. When fracture occurred, the test was removed from the machine and the force level and fracture type was noted.

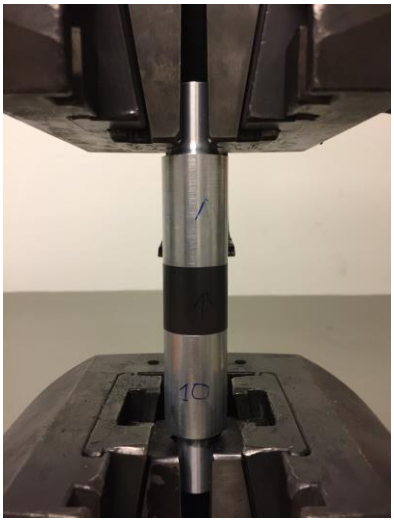


Figure 35: Tensile Test

2.3.1.3.1 Room temperature

The bulk of the tests were preformed in room temperature. The tests were prepared as above and then pulled in room temperature, see Figure 36.

Figure 36: Tensile test performed in Amsler.

2.3.1.3.2 Reduced Temperature, -30° C

Figure 37: Tensile test right out of the freezer.

The components were joined and cured in the ordinary way but then put in a freezer at -30 degrees Celsius for minimum 16 hours, see Figure 37. The object was then put in place in the tensile test machine and the surface temperature was measured. The objects were exposed to tensile stress until fracture. Directly after the fracture, the inner temperature of the test object was measured and the force level was noted.

2.3.1.3.3 Elevated temperature, 125° C

Two of the adhesives were tested in elevated temperature, 125° C. The test objects were prepared in the ordinary way but later on put in an oven and heated up to the requested temperature, 125° C, for minimum of 2 hours. The objects were then brought directly from the oven to the test machine, preforming the test on heated components. The objects were exposed to tensile stress until fracture. Directly after the fracture the inner temperature of the test object was measured with *62 mini IR Thermometer FLUKE, ID: 6558*. The force level was noted.

2.3.1.3.4 Elevated Temperature, 155° C

Two of the adhesives were tested in even higher temperature, 155° C, just to figure out what would have happened if the engine was introduced to a temperature peak. The objects were performed in the ordinary way and then put in a pre-heated oven for two hours. The oven temperature was measured with the *62 mini IR Thermometer FLUKE, ID: 6558*.

The objects were exposed to tensile stress until fracture. Directly after the fracture the inner temperature of the test object was measured. The force level was noted.

2.3.1.4 Die and punch side

The die- and punch tests were only performed with the cyanoacrylate, Permabond 820, which went on into further investigations. The tests were performed on rectangular components out of 1P and 5P, called TRS and IE. During the gluing process, five components were placed on the side so that the die side got the glue, and five components were placed in the ordinary was so that the punch side got the glue. The tests were performed on one material at the time. The five parts that were representing the punch side got the edges removed. See Figure 38.

Figure 38: Die- or Punch side tensile tests on 1P. Left: five die side Right: five punch side

2.3.1.5 Adhesive Maximum

To test the maximum stress level of the adhesives it was applied to two aluminum surfaces, without any SMC in between. The test was made as an addition to the safety data sheets and the results were compared to get an understanding of the actual case.

The objects were prepared in the usual way, glued in the aluminum fixture and cured at recommended time and temperature. Then tested in *Amsler dragprovare* and pulled until failure. However, only the two adhesives that went on in the process were tested.

2.3.1.6 Rotation

To make sure that the magnets would not fall out during run, the rotation forces were calculated and compared to the safety data sheets of the adhesives that made it through the testing face. The design of the stator was simplified so that the outer diameter of the rotor was representing the outer diameter of the magnet even though the magnet is placed some millimeters in. The calculations were made as follows, see Figure 39:

$$F_c = ma \tag{2.8}$$

$$F_c = mw^2 r_{\perp} \tag{2.9}$$

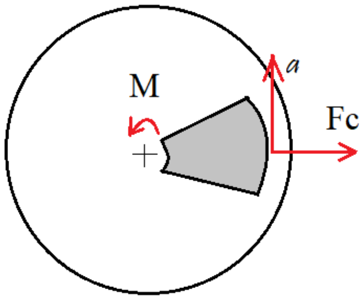


Figure 39: Schematic figure of the forces applied on the magnet during run.

To convert the force into stress and MPa, to be able to compare it to the data sheet, the shear area was calculated, as the area under the magnet.

$$A_{rotor} = \pi r^2 \tag{2.10}$$

$$A_{rotor_i} = \pi {r_i}^2 \tag{2.11}$$

$$A_{magnet} = \left(A_{rotor} - A_{rotor_i}\right) * a \tag{2.12}$$

Where a is the angle of the magnet, see Figure 40.

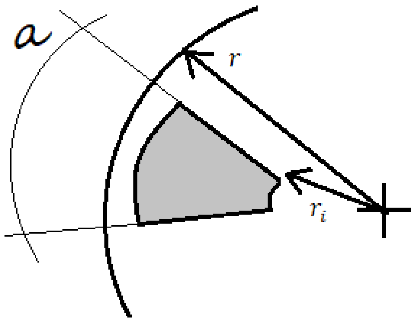


Figure 40: Schematic figure of the placement and the angle of the magnet.

The shear stress in the adhesive under the magnet was then:

$$\tau = \frac{F_c}{A_{magnet}} \tag{2.13}$$

2.3.1.7 Evaluation and Selection

A test was sent to metallography department at *Höganäs* to check if the adhesive had penetrated the substrate and maybe created a stronger bond.

A major time was then spent to evaluate the results made from the first tests, and to select the different adhesives that would be further investigated. The selections depended on the obvious results from the tests but also parameters such as price, health issues, environmental aspects and availability.

From the tests made in room temperature, with and without grinded surface, it was possible to see that some adhesives did worse than the other. Some was unpredictable and was therefore removed from further investigation.

A discussion was held to be able to decide which adhesive to move on with. In addition to the discussion, a table was made, containing the most important requests and information about the adhesives, se*e Table 2* in *Appendices.* From this table it was decided to move on with L2 and L5, the *Permabond ES550* and the *Permabond 820*. These two were also picked because of their structure, one being an epoxy and the other one a cyanoacrylate, see *Results* and *Discussion*.

2.3.2 **Crimping**

The crimp tests were made with real stator components and an aluminum housing. The area of the edge of the stator was measured and calculated as follows to be able to see how big of a pressure it could take.

$$A = d * \pi * h \tag{2.14}$$

Where d was the diameter of the biggest stator and h was the height of the edge, found on drawings. On the drawings, the edge of the stator (of three millimeters) was tilted for two millimeters and vertical for the last one, making it hard to tell how big of an attachment surface or “grip surface” there would be in the real scenario, see Figure 41. The height, or grip surface, was estimated to the averge of $h = 2\ mm$.

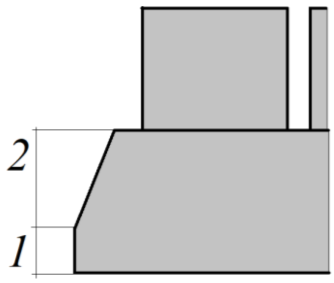


Figure 41: Schematic illustration of the edge of the stator.

The stress was calculated as:

$$\tau = \frac{F}{A} \tag{2.13}$$

Where F was the force measured in the machine, being the friction force between the two surfaces and A the area from above.

2.3.2.1 The making of the Crimp Tests

The aluminum housing was placed in an oven at 237° C for one hour and then placed over the block. The stator was lowered down inside the housing. It was placed upside down, at lowest height possible, see Figure 42.

After each test, the stator component was placed higher and higher, with help from the block and screws, to make sure that the attachment surface was unharmed and without scratches from previous tests. Seven tests were performed. The last test was not placed upside down, but on the very top of the housing to demonstrate how the stator would behave if the teeth was not locked in.

Figure 42: Stator, crimped inside the Aluminum housing.

2.3.2.2 Verification of test method

For the crimp tests, there were no room for verification. The aluminum housing was expensive and time consuming to create and manufacture, which made every single test count. However, the results of the seven test, ended up being important in different aspects of the investigation, see *Results* and *Discussion*.

2.3.2.3 The Crimp Tests

When the stator component was placed at a correct position, inside the aluminum housing, and the housing had cooled down, the two objects were placed in the upper part of the *Amsler dragprovare*, ID: *4459*, making it possible to press, instead of pulling, see Figure 43.

The machine settings were as follows:

- Small piston (lilla kolven): 1
- Measurement (mätring): 98kN
- Hole setting (hålinställning): I

The settings made it possible to measure newtons at a 1 to 1 scale. The plastic cylinder was placed on top of the stator and the machine was started, see Figure 44.

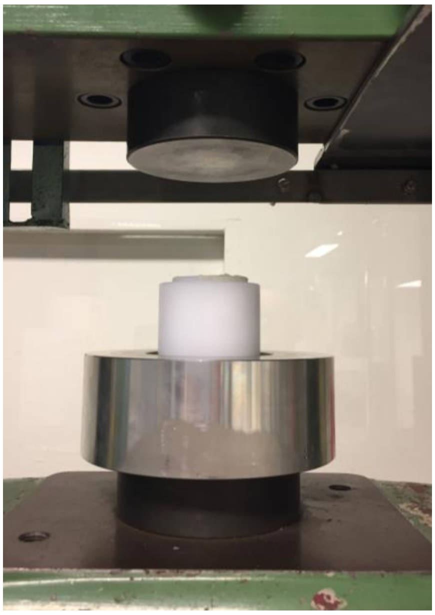


Figure 43: Arrangement for Crimp Test.

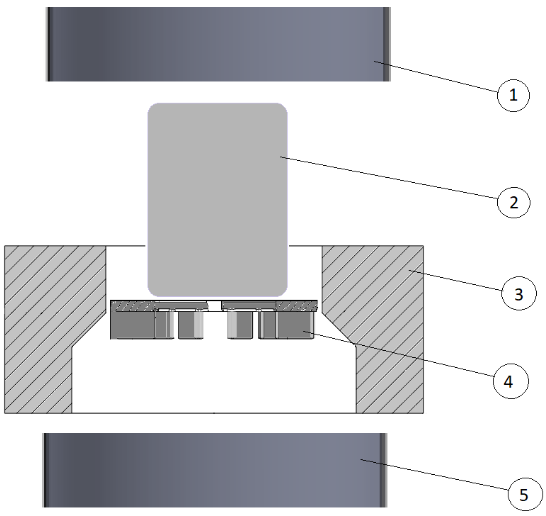


Figure 44: 1. Upper Press 2. Plastic cylinder 3. Aluminum housing 4. Stator component 5. Lower press

2.3.3 **Clamping**

For the clamping, calculations were made to see how wide the edge would have to be to be able to hold the required forces. The limitations of the *Somaloy®* was taken into consideration. Gravity was not taken into consideration. The force situation was simplified to be represented by an outspread force of $Q = 270\ N$ over the whole construction. The stator was simplified to be a slender beam put on two supports. The clamping situation was simplified as can be seen in Figure 45. Calculations were made as follows:

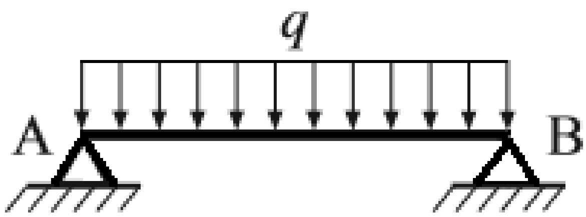


Figure 45: Simplified clamping situation.

The support forces would then be:

$$R_A = -\frac{qL}{2} \tag{2.14}$$

$$R_B = -\frac{qL}{2} \tag{2.15}$$

Where L is the length between the two supports. The shear force and the torque would then be:

$$V = q\left(\frac{L}{2} - x\right) \tag{2.16}$$

$$M = \frac{q}{2}\left(-Lx + x^2\right) \tag{2.17}$$

As seen in Figure 46, the shear force reaches its maximum in the very ends of the construction, right above the supports. This gives that the maximum shear stress equals the shear force divided by the shear area. The area is hard to simplify, but it was seen as a rectangle with the same width as thickness, giving:

$$A = b * h = 3 * 3 \tag{2.18}$$

The calculated maximum shear stress was compared with the transvers rupture strength of the material in the data sheets [24].

It can be seen in Figure 47 that the torque reaches its maximum in the middle of the construction [25].

Figure 46: Shear stress in the simplified clamp construction.

Figure 47: Torque in the simplified clamp construction.

Other than the stator, being able to hold the shear stresses provided by single supports in the ends, it would also need to hold for the pressure and stress on the surface of the edge, see Figure 48.

This would give how big of an edge it would take to hold the stator, without damaging the stator during run.

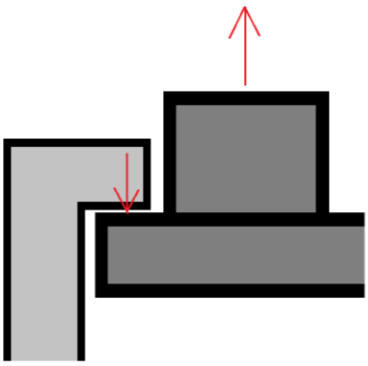


Figure 48: showing the reaction force on the surface.

The new diameter was calculated as follows:

$$A_{stator} = \pi \left(\left(\frac{d_y}{2}\right)^2 - \left(\frac{d_i}{2}\right)^2 \right) \tag{2.19}$$

$$\sigma = \frac{F}{A} \tag{2.20}$$

$$=> A_{req} = \frac{F}{\sigma} \tag{2.21}$$

$$A_{new} = A_{stator} + A_{req} \tag{2.22}$$

$$A_{new} = \pi \left(\frac{d_{new}}{2}\right)^2 \tag{2.23}$$

$$=> d_{new} = 2\sqrt{\frac{A_{new}}{\pi}} \tag{2.24}$$

Where A_{stator} was the actual area of the stator, and A_{req} the required one for being able to withstand the pressure. The required area could be placed in different positions around the stator, however, for this projects it was imagined to be spread all around the edge of the stator. The new diameter of the stator, the d_{new} was the measurement across the new area, A_{new}, see Figure 49:

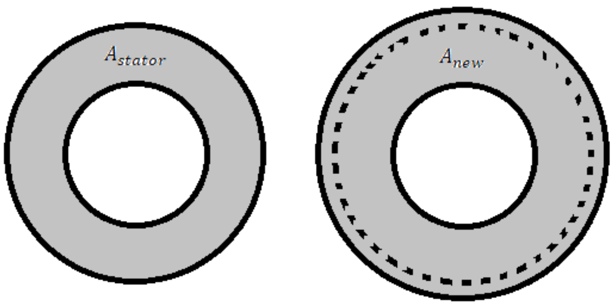


Figure 49: Schematic figure of the areas, before and after introducing the required edge.

3 Results

In this chapter, the results from testing and calculations will be presented.

3.1 Tensile Tests

The results from the tensile tests are placed in chronological order and put in chapters depending on the test temperature. The final results will be presented in Figure 79 and Figure 80, where the stress levels, of the adhesives that made it into further investigations, are plotted against the temperatures.

3.1.1 **Room Temperature, 24° C**

From the tensile tests, made and run in room temperature, four adhesives were stated as reliable and two as unpredictable. For the four adhesives, stated as reliable, the surface treatment did not make any difference for the stress level results.

There turned out to be three different types of fracture, see Figure 50.

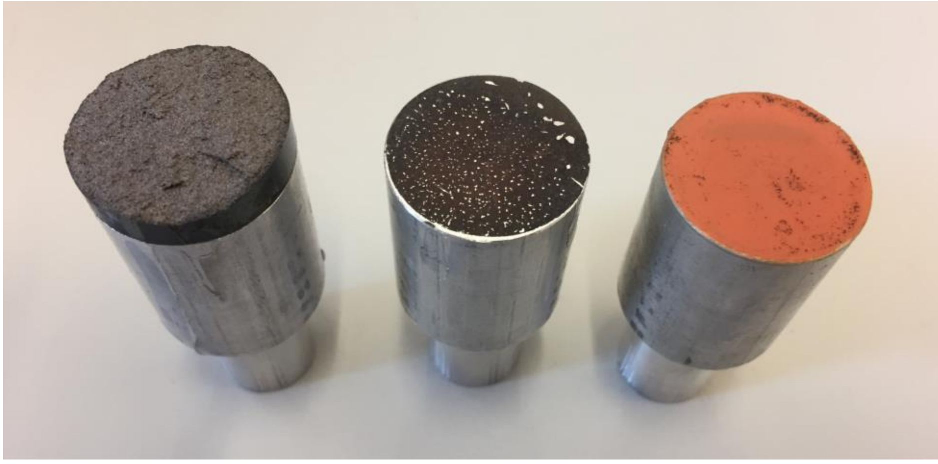


Figure 50: Three types of fracture.

The most obvious, and the most common, fracture type was the SMC failure, where the fracture occurred in the SMC. The fracture happened when the tensile stress exceeded 3.3 MPa for 1P and 7.0 MPa for 5P. (The values are averages drawn from every test where SMC failure occurred.) See figure 51.

Figure 51: SMC failure.

Figure 52: Adhesive failure

The second most common fracture was the adhesive failure, where the adhesive did not attach to the surfaces, creating a fracture. The fracture type happened for two of the adhesives at unpredictable stresses. The average was 2 MPa for 1P and 3 MPa for 5P (Average drawn from all of the objects where adhesive fracture occurred.) See Figure 52.

The third fracture type was the substrate surface coating fracture, SURF, where the top layer of the SMC was ripped. See Figure 53. The fracture only occurred on ruff surfaces. It did not occur on the grinded surfaces. However, the fracture occurred at the same stress level as the SMC failure, and it was sometimes hard to tell if it was going to be a SURF or a SMC failure, due to the elevated stress level.

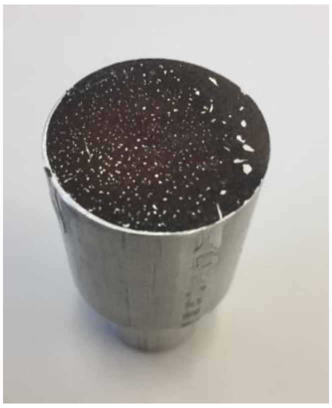


Figure 53: SURF failure.

Figure 54: SURF failure on rough 5P. L1 at room temperature.

3.1.1.1 Loctite 648

The combination of *Loctite 648*, *Loctite SF7471* and *Loctite SF7063* did well in the room temperature tests. The adhesive was stronger than the SMC, which was shown by SMC failures on grinded components and SURF failures on ruff components. See Figure 54. The stress level is shown in Figure 60.

3.1.1.2 Permabond ES550

The Permabond 550 did exceptionally in the room temperature tests. The products was easy to work with, it cured in the right time and was ready for testing right out of the oven. The adhesive was stronger than the SMC and the epoxy was believed to interact with the aluminum to make an even stronger bond, which was shown by a SMC failure [7]. See Figure 55. The stress level is shown in Figure 60. It was decided to continue with the adhesive in further investigations.

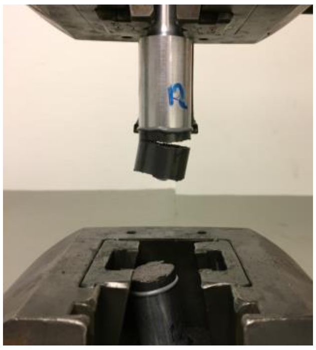


Figure 55: SMC failure. L2

3.1.1.3 Permabond ES562

The *Permabond ES562* did as well as the others when the surface was grinded, but when tested on ruff surfaces the adhesive was unpredictable and created adhesive fractures at different stress levels, see Figure 56. The average stress level is shown in Figure 60. It was decided to remove the adhesive from further testing due to it being unpredictable.

Figure 56: Adhesive failure on ruff surface. L3

Figure 57: SMC failures. L4

3.1.1.4 Araldite AV4600

Araldite AV4600 did well in the room temperature tests. The adhesive was stronger than the SMC, which was shown by SMC failures, see Figure 57. The stress level is shown in Figure 60.

However, the adhesive did not cure at the time stated in the material data sheet. It had to be re cured for another hour.

3.1.1.5 Permabond 820

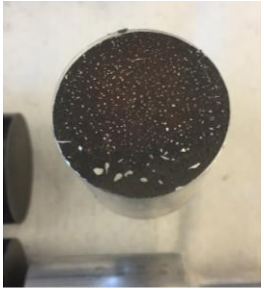


Figure 58: SURF failure on 5P, L5.

The *Permabond 820* gave the highest values for the 5P material. It was as good as the other adhesives on 1P and did not make any difference on the ruff surfaces. The adhesives was stronger than the SMC resulting in SMC failures and SURF failures, see Figure 58. The stress level is shown in Figure 60. It was decided to continue with the adhesive into further investigations.

3.1.1.6 Permabond HH131

The *Permabond HH131* did not do well in the tests. The adhesive had some of the lowest scores and adhesive failures occurring at unpredictable stress levels. In one half of the tests the adhesive had not attached to the aluminum, and on the other half it had not attached on the SMC, see Figure 59. The average stress level is shown in Figure 60. It was decided to remove the adhesive from further testing due to it being unpredictable.

Figure 59: Adhesive failure L6.

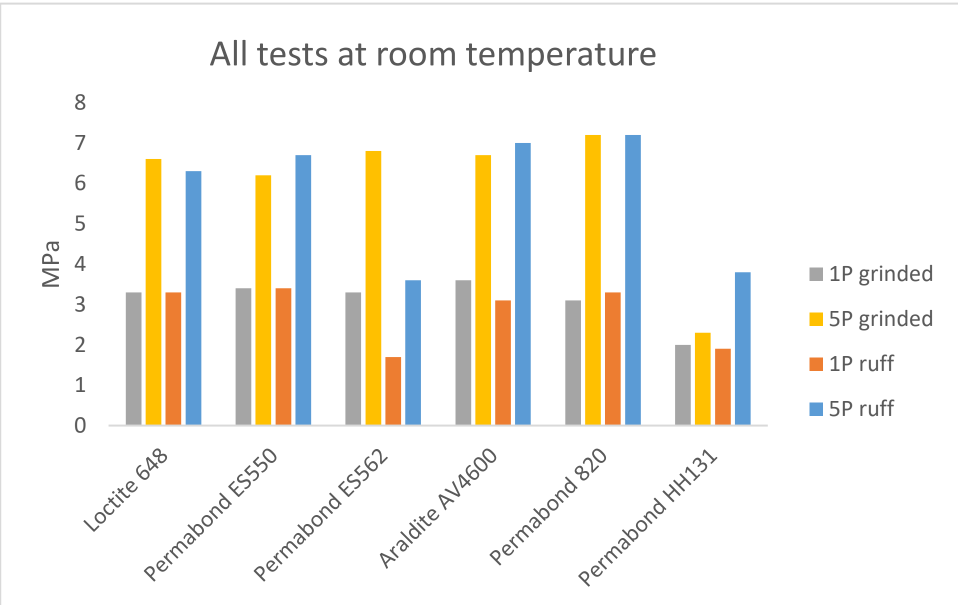


Figure 60: All tests in room temperature, showing the average stress level of each material and surface treatment, for every adhesive. (Average is drawn out of five tests in each category.)

3.1.2 Reduced Temperature, -30° C

For the tensile tests performed in reduced temperature, two adhesives were used: *Permabond ES550* and *Permabond 820*. The SMC surfaces were not grinded but the edges were removed.

Right after the fracture, the inner temperature of the test object was measured. It was noted that the temperature was below zero but rapidly rising making it impossible to state the actual inner temperature during the test.

3.1.2.1 Permabond ES550

When Permabond ES550 were tested in reduced temperature, the adhesive were still stronger than the SMC, showed with SMC failures, see Figure 61. The tensile stress levels for the test preformed in reduced temperature can be seen in Figure 63.

Figure 61: SMC failure. L2 in reduced temperature.

Figure 62: SURF failure on 5P. L5 at reduced temperature.

3.1.2.2 Permabond 820

The cyanoacrylate *Permabond 820* were stronger than the SMC when tested in reduced temperature. For the 1P material, SMC failures occurred and for the 5P material, there were a majority of SURF failures, see figure 62.

The tensile stress levels for the test performed in reduced temperature can be seen in Figure 63.

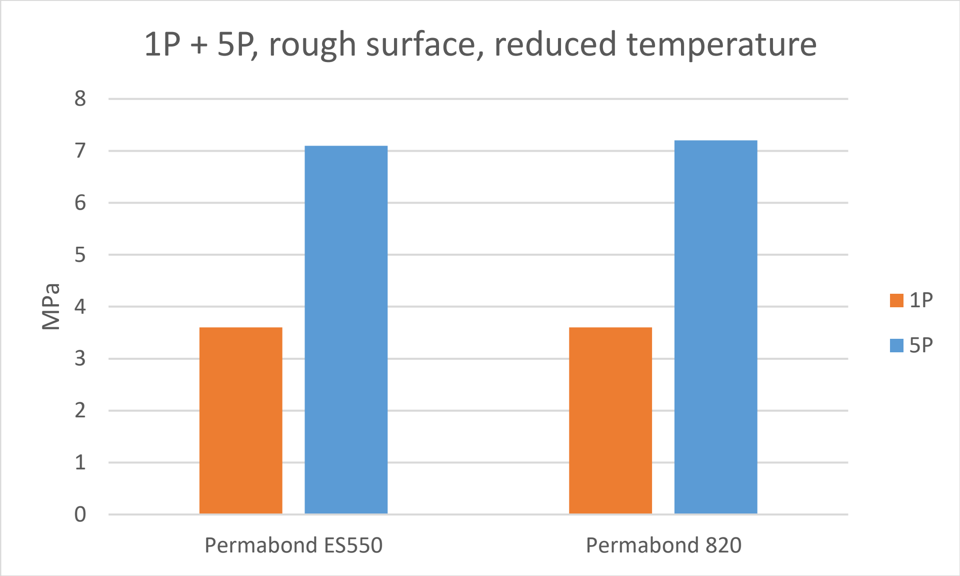


Figure 63: All tests conducted at the reduced temperature. Showing the average stress level for each material and adhesive. (Average drawn out of five tests in each category)

3.1.3 **Elevated temperature, 125° C**

For the tensile tests performed in elevated temperature, 125 degrees Celsius, two adhesives were used: *Permabond ES550* and *Permabond 820*. The SMC surfaces were not grinded but the edges were removed.

Right after the fracture, the inner temperature of the test object was measured. It was noted that the temperature was above 60° C but rapidly decreasing making it impossible to state the actual inner temperature during the test.

3.1.3.1 Permabond ES550

When Permabond ES550 was tested in elevated temperature, the adhesive was stronger than the SCM, showed by a SMC failure, see Figure 64. The results were as the ones in room temperature, if somewhat a bit higher for the 5P material.

The tensile stress levels for the test preformed in elevated temperature can be seen in Figure 67.

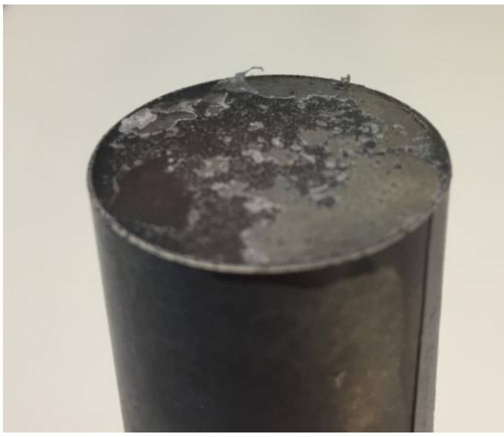
Figure 64: Elevated temperature, 125° C, L2.

3.1.3.2 Permabond 820

When the adhesive was applied on 1P it did not show any weakness, the adhesive was stronger than the 1P material, showed by SMC failures.

The adhesive applied on 5P showed that, even though it was stronger than requested, the heat affected it and it turned out bubbly in some of the tests. There were SURF failures and/or adhesive failures where the adhesive was coming of as flakes at a relatively low stress level, see Figure 65 and Figure 66.

The stress levels are showed in figure 67.



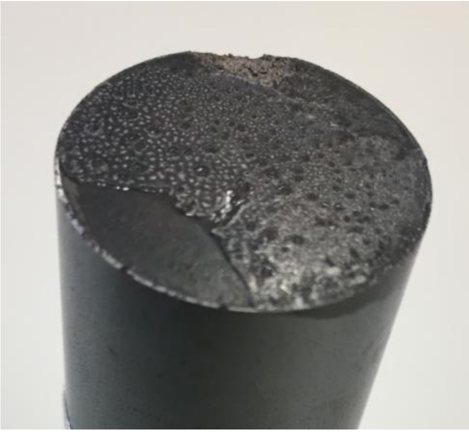


Figure 65: The adhesive is coming out as flakes. Figure 66: The adhesive is affected by the heat.

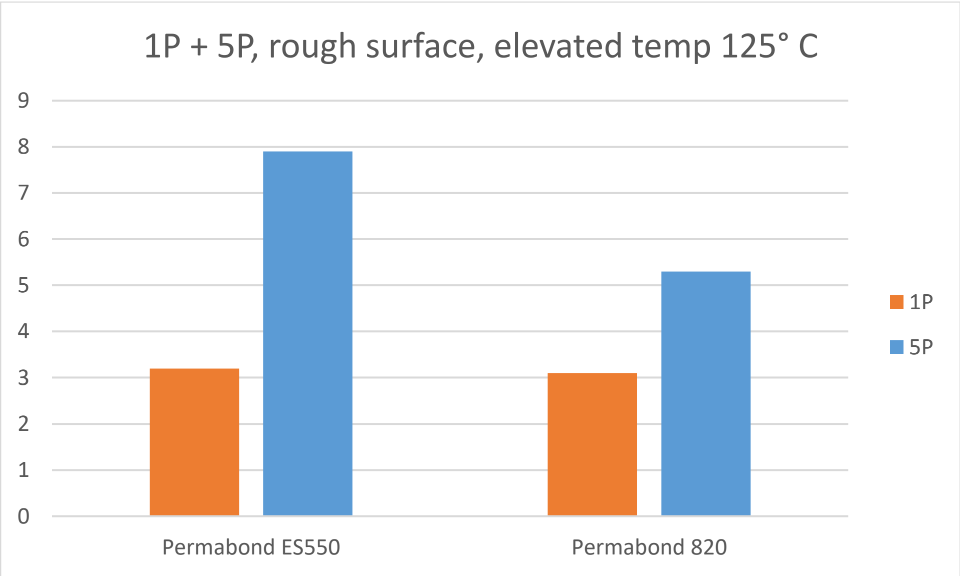


Figure 67: All the tests were performed at the elevated temperature of 125° C. The average stress level for each material and adhesive is shown. The average value is based on five tests in each category.

3.1.4 **Elevated temperature, 155° C**

For the tensile tests performed in elevated temperature, 155 degrees Celsius, two adhesives were used: *Permabond ES550* and *Permabond 820*. The SMC surfaces were not grinded but the edges were removed.

The measured temperature on the surface of the objects were 155° C while in the oven. Right after the fracture, the inner temperature of the test object was measured. It was noted that the temperature was above 110° C but rapidly decreasing making it impossible to state the actual inner temperature during the test.

Figure 68: SURF and/or adhesive failure.

3.1.4.1 Permabond ES550

When Permabond ES550 was tested in the highest temperature it got affected for the first time; on the 5P material there were a majority of SURF and/or adhesive failures at a relatively low stress level, see Figure 68. The 1P material gave SMC failures. The stress level can be seen in Figure 70:

Figure 69: Adhesive failure, L5.

3.1.4.2 Permabond 820

The *Permabond 820* did poorly in the highest temperature tests. Some of the test objects broke while tightening due to the small forces and adhesive failure.

It cannot be recommended to use this adhesive if the construction reaches 155 degrees.

In Figure 69 the bubbly adhesive surface can be seen.

The average tensile stress level is presented in Figure 70.

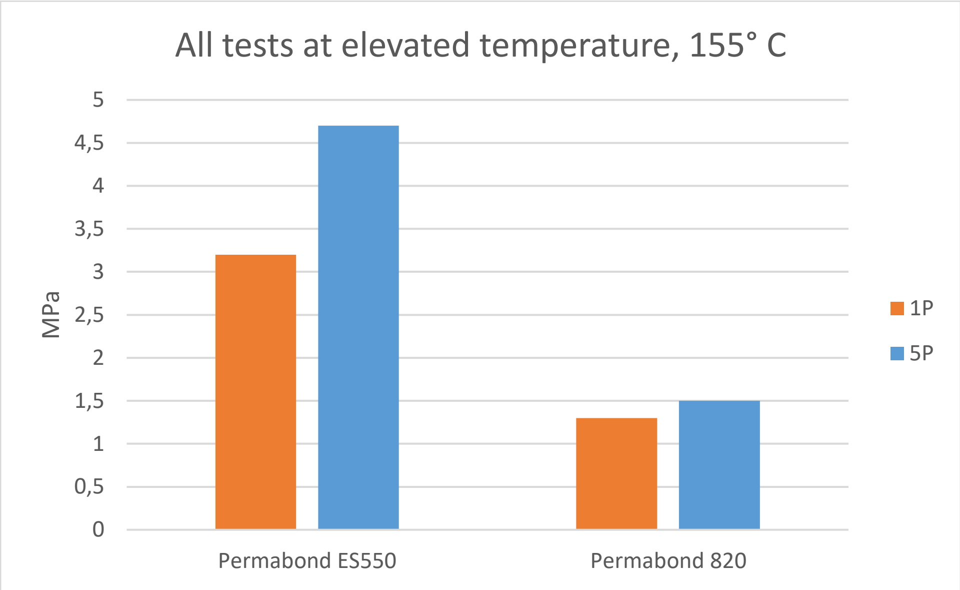


Figure 70: All the tests were performed at the elevated temperature of 125° C. The average stress level for each material and adhesive is shown. The average value is based on five tests in each category.

3.1.5 Die- or Punch side

The test made on different sides of the component showed that the adhesive is more likely to attach to the punch side, rather than the die side. This was shown by SMC failures when testing on punch side and SURF- and adhesive failures when testing on die side, se Figure 71, Figure 72, Figure 73 and Figure 74.

For the 1P material (the TRS component) the stress levels were similar in both tests but the fracture was different. When the adhesive was attached to the punch side the SMC component had a fracture straight through, but the joints were solid. Then, when the adhesive was attached to the die side, there were clear SURF failures.

Almost the same happened to the 5P components, (the IE). When the adhesive was attached to the punch side, there were clear SMC failures and when the die side was tested the surface came off, or the adhesive had not attached to the surface.

The average stress levels are shown in Figure 75. It can be seen that even though there were SURF and adhesive failures, the average stress levels are relatively high, appearing at the same level as the SMC failure for the 1P material, however, the stress from the test of punch side on the 5P material is twice the size.

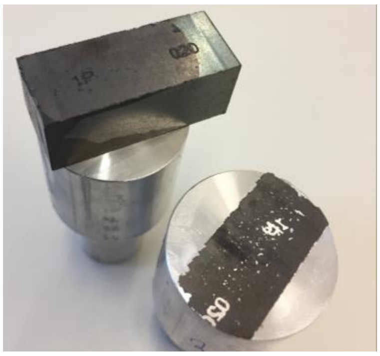


Figure 71: Die side, 1P TRS.

Figure 72: Punch side, 1P TRS.

Figure 73: Die side, 5P IE.

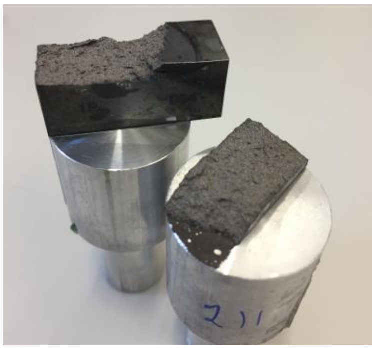


Figure 74: Punch side, 5P IE.

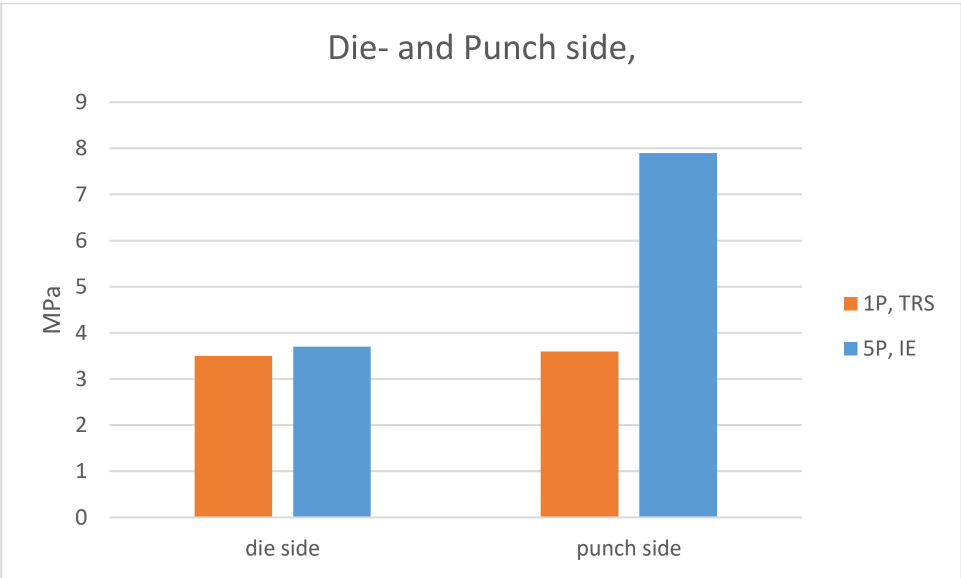


Figure 75: Tests performed for the Die- and Punch side. Showing the average stress level for each material and joining side. (Average drawn out of five tests in each category)

3.1.6 **Adhesive Maximum**

3.1.6.1 Permabond ES550

In the safety data sheet, for the *Permabond ES550*, it can be seen that it should have a shear strength of $17 - 31\,MPa$ when applied on aluminum. The tensile stress is not stated.

From the tensile tests, it was shown that the adhesive could hold $41.2\,MPa$ and a force of $F = 20189\,N$ on an average.

There was so called real adhesive failure, meaning that the adhesive broke because of it reaching its limit, not because of it not attaching to the aluminum surface, see Figure 76.

Figure 76: Real Adhesive Failure. L2 on aluminum.

3.1.6.2 Permabond 820

In the safety data sheet, for the *Permabond 820*, it is stated that the adhesive should have a shear strength of $19 - 23\,MPa$ when applied on steel. The tensile stress is not stated, nether is the shear strength when applied on aluminum.

From the tensile tests, it was shown that the adhesive could hold $4.6\,MPa$ and a force of $F = 2234\,N$ in average, when applied on aluminum. (The ordinary tensile tests show that the adhesive is stronger when applied on aluminum and SMC.)

There was adhesive failure, see Figure 77.

Figure 77: Adhesive failure. L5 on aluminum.

3.1.7 Rotation

From the rotation calculations it was stated that the force created by the rotation would be $F_c = 31\ N$. The area under the magnet was $162\ mm^2$. The shear stress in the adhesive, underneath the magnet, was then $\tau = 0{,}19\ MPa$.

The adhesives that went on into further investigations had shear stresses around $\tau = 20\ MPa$, which gives that the shear stress applied on the magnet due to rotation is about one percent out of what the adhesive can take.

3.1.8 Substrate penetration

There was no sign that the adhesive had penetrated the substrate. In the close up pictures there could be seen some black sports, but this were taught to be residues from pressing. The adhesive was seen as a grey substrate, between the smooth aluminum and the ruff SMC, see Figure 78.

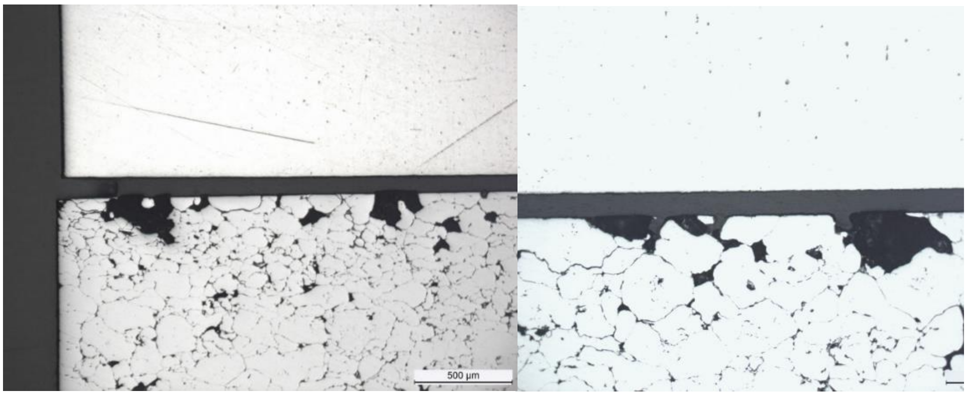


Figure 78: The joint between aluminum and SMC, 5P.

3.1.9 Verification of test method

It was important to remove the edges or the adhesive would not have contact with the entire surface.

It did not make any difference what side of the puck that was up during the gluing process, the failure would mostly occur on the least ruff surface anyway.

3.1.10 **Final Tensile Test Results**

According to the test results, it is possible to use gluing as an attachment method for the rotor and the stator. The epoxy, *Permabond ES550*, and the cyanoacrylate, *Permabond 820*, can be used. However, the *Permabond 820* should not be used if it is possible to believe that the run temperature may peak up to 155 degrees. Figure 79 and Figure 80 shows the two adhesives and their stress levels in the different temperatures.

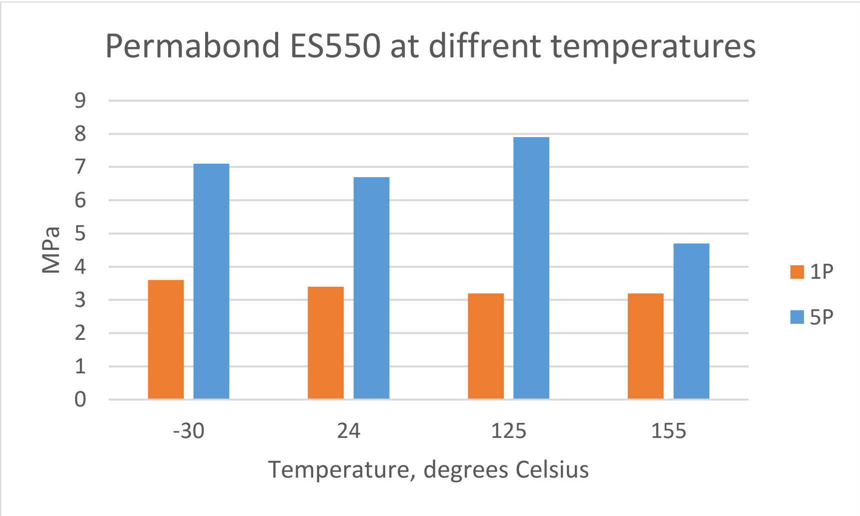


Figure 79: *Permabond ES550* at different temperatures. (Average drawn out of five tests in each category)

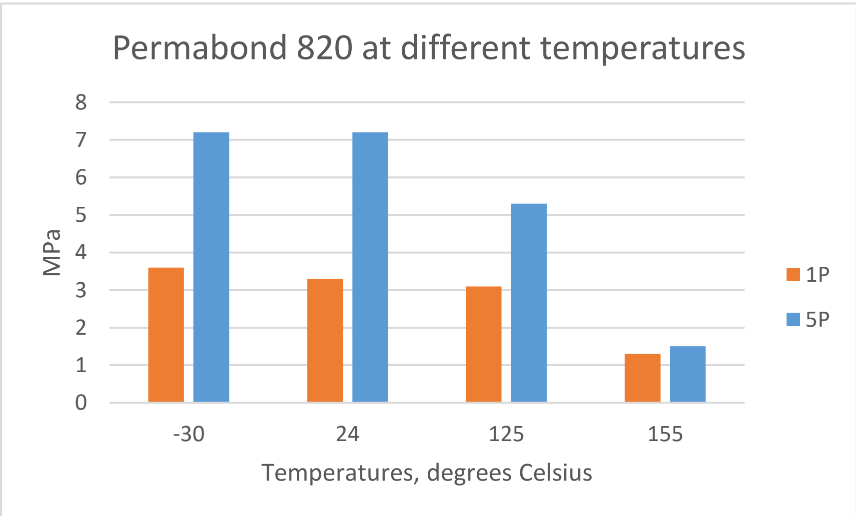


Figure 80: *Permabond 820* at different temperatures. (Average drawn out of five tests in each category)

3.2 Crimp Tests

In this chapter, the results from the crimp tests and the crimp calculations will be presented.

3.2.1 **Calculations**

The crimp calculations were made to calculate the inner diameter of the crimp test fixture and the expected force level.

When the diametrical grip was set to $\Delta = 120\ \mu m$ the inner diameter of the fixture was $D = 64{,}879\ mm$. This gave the force $F = 767\ N$.

The inner diameter of the housing, when heated up, was calculated to be $D_{heat} = 65{,}223\ mm$

The average area of the edge of the stator was $A = 408\ mm^2$.

3.2.2 **Crimp Tests**

The aluminum housing was measured to $D = 64{,}883\ mm$ before heating. Since the diameter of the first test stator was $d = 65{,}005\ mm$, the diametrical grip turned out to be $\Delta = 0{,}122\ mm$ or $\Delta = 122\ \mu m$.

The diameter of the housing after heating was $D_{heat} = 65{,}117\ mm$. The housing was heated up to a temperature of $T = 237°$ degrees Celsius, for $t = 40\ min$. This gave a diametrical gap (between the housing and the stator) of $g = 0{,}112\ mm$.

The stator could easily slide in place and was fixed within two minutes. The housing had to be cooled down for up to three hours.

The stators placed in the middle of the aluminum housing had to slide on the inside to be able to fall out. It was decided through discussions that it would be the first force disturbance that represented the actual failure, and not the force that made the stator fall out of the housing.

3.2.2.1 Crimp test Nr1

The first test showed that a construction as this one can take stress levels way higher than requested. However, the stator component was bended and cracked due to the plastic cylinder being too slender, see Figure 81. The component fell out of the housing at a force of $F = 2605\ N$ and.

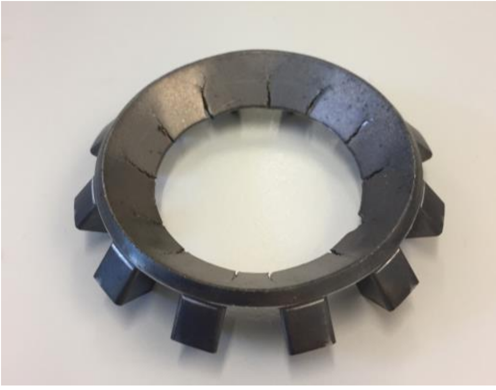


Figure 81: Stator from Crimp test Nr1.

3.2.2.2 Crimp test Nr2

A thicker plastic cylinder was used. During press, the component slided on the inside of the housing making it hard to tell when the actual fracture occurred. There were disturbances in the force around $F = 5000\ N$. The stator fell out of the housing at a force of $F = 7415\ N$. When it fell out it was bended but without cracks, some slide marks on the teeth, see Figure 82.

Figure 82: Stator from Crimp test Nr2.

3.2.2.3 Crimp test Nr3

The stator was not entirely horizontal when attached. The force measurement was filmed to be able to see when disturbances occurred. There were disturbances at $F = 1650\ N$, $F = 2600\ N$ and $F = 2600\ N$. The stator fell out at $F = 4490\ N$. It had slided a long way against the inside of the housing and was therefore demolished on the sides, see Figure 83.

Figure 83: Stator from Crimp test Nr3.

3.2.2.4 Crimp test Nr4

The force measurement and underneath the stator, was filmed to be able to see when disturbances occurred. Figure 85.

However, almost no disturbances occurred but a small decrease of the speed at $F = 3000\ N$.

When the stator fell out the upper edge was ripped off and the inside of the aluminum housing was changed into a more ruff surface, see Figure 84. The stator fell out at $F = 3470\ N$.

Figure 84: Stator from Crimp test Nr4.

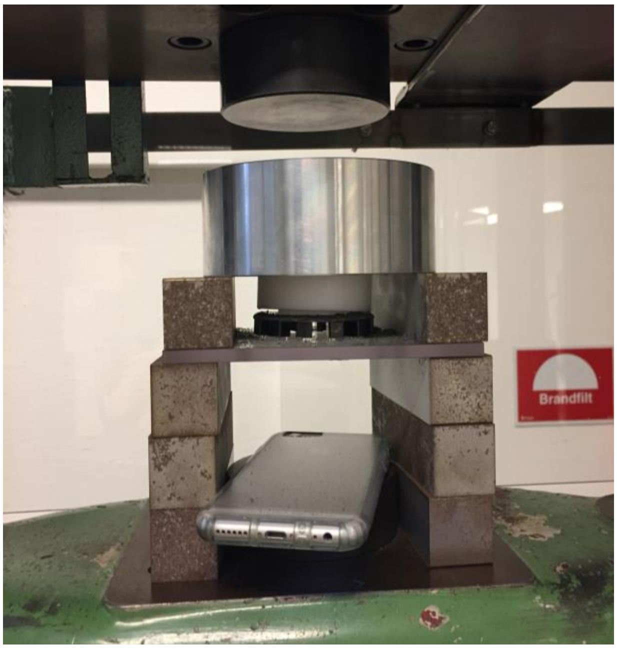


Figure 85: Filming under the stator to detect disturbances.

3.2.2.5 Crimp test Nr5

The test was filmed and logged with a graph (force x elongation), see Figure 87. It was the test with least disturbances but from the graph, it can be seen that there is something happening around $F = 1300\ N$ and then again around $F = 2700\ N$. The stator fell out at $F = 3525\ N$. The edge of the stator was ripped off, see Figure 86.

Figure 86: Stator from Crimp test Nr5.

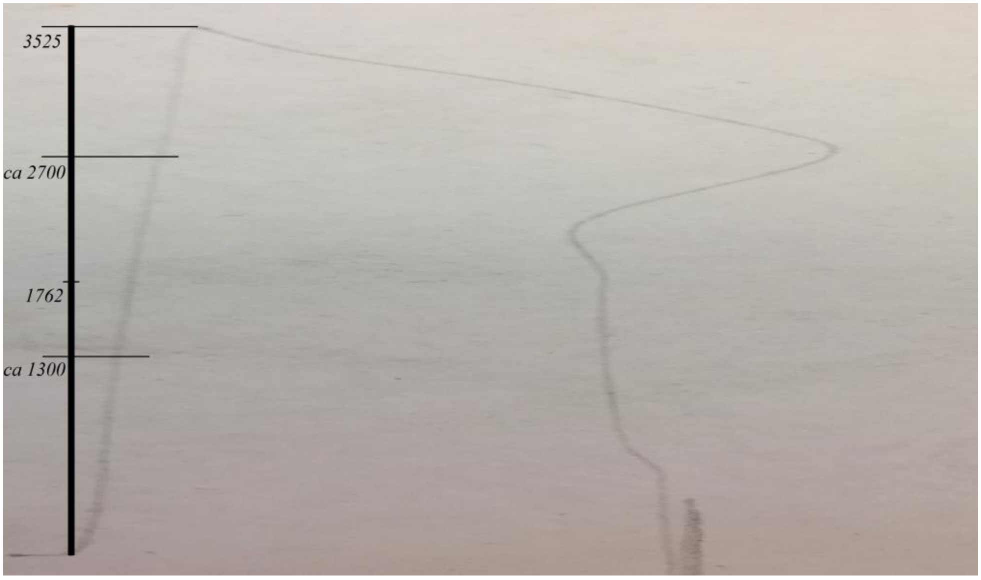


Figure 87: Graph from crimp test Nr5. Stator from Crimp test Nr5.

3.2.2.6 Crimp test Nr6

The test was filmed and logged with a graph (force x elongation). From the graph it can be seen that the force is going straight up to $F = 1150\ N$, when it suddenly starts to differ and move in an odd way, see Figure 89. The stator fell out at $F = 2290\ N$. The edge of the stator was ripped off, see Figure 88.

Figure 88: Stator from Crimp test Nr6.

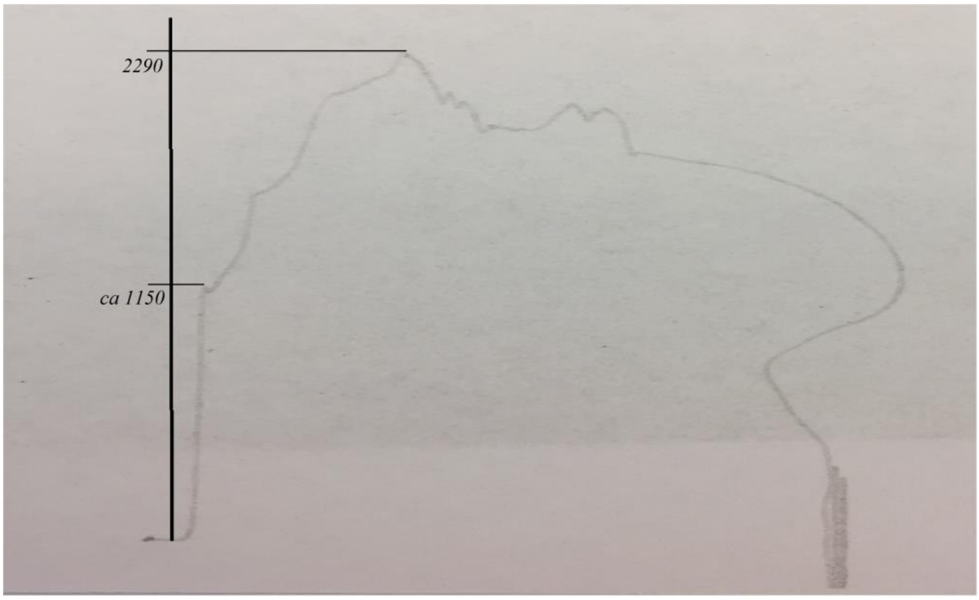


Figure 89: Graph from Crimp test Nr6.

3.2.2.7 Crimp test Nr7

Since the stator was placed in a different way compared to the other, it did not have the possibilities to slide against any sides, it just fell right out. The force, when falling out, was measured to $F = 1815\ N$. The stator was almost intact, see Figure 90.

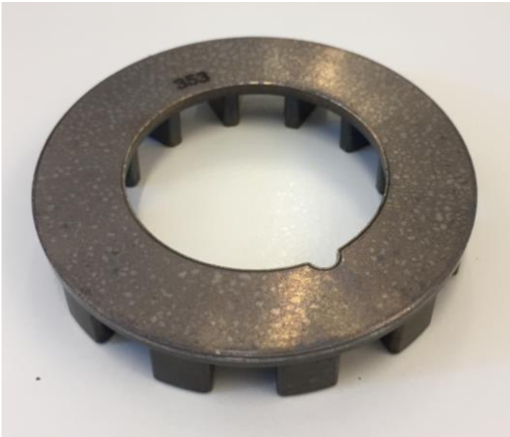


Figure 90: Stator from test Nr7.

3.2.3 **Final Crimp test Results**

From the crimp tests, it was shown that a construction like this could hold an average force of $F = 2360\ N$ and an average stress of $\tau = 5{,}8\ MPa$, in room temperature. (Average draw out of the seven tests and the first visual disturbances in each test.)

3.3 Clamping Calculations

From the clamping calculations, it was stated that the new, required area, to stand for the pressures of the supporting step, had to be $A_{req} = 2{,}45\ mm^2$.

If the required area was placed as an edge all the way around the existing stator, the new diameter would be $d_{new} = 65{,}02\ mm$.

The maximum shear stress was $\tau = 15\ MPa$. Maximum shear stress from the data sheet was $\tau = 60\ MPa$.

4 Discussion

In this chapter, the results and different choices will be discussed. Possibilities for further investigations will also be stated.

4.1 Attachment methods

The project started out with major discussions on what attachment methods were going to be investigated. The ones that were selected, gluing, crimping, and clamping were considered the best methods due to the current design of the engine. However, if clamping were supposed to be used, the engine had to be re designed. For example, the construction would require an edge on the stator, meaning making a new design.

Instead, it was decided to work more with gluing and crimping, which could be applied on the current rotor and stator design. However, if the crimping was to be decided for, the housing, or material around the stator had to be redesigned, but that was considered a minor problem at the moment, since that design process was still running.

4.2 Tensile Tests

There are plenty of parameters that could be discussed when it comes to the tensile tests. As a start, the machine used was not very tight in its parts and could therefore slide in different directions, introducing bending to the tests. It was discussed whether the machine needed a construction to eliminate the bending, such as a cardan/universal joint, but the broad validation of tests showed that the results were even, even though the test objects were bended and placed off center.

Another parameter is the surface treatment of the aluminum cylinders. The first tests were made with aluminum cylinders that came directly form the reseller. However, these tests were only used as a validation of the test method, and not taken into account while looking at the results. Soon, the surface of the aluminum cylinder were grinded by hand to make sure that everyone was equal. When the cylinders were up, they were reused; they were run through the lathe machine and used again.

While discussing with the machine operator, it was found that the lathe machine used a lubricant and then ethanol to be able to operate the surface [26]. It is possible to believe that this would make a difference for the attachment of the components; however, no differences or conclusions could be drawn from the results concerning this. It is also possible that the components made in the future will be treated in different ways, depending on companies and scale; one can then say that these adhesives will possibly work, regardless of whether the aluminum surface is lathed in a CNC machine or grinded by hand.

The fact that there were a slightly higher value, when testing in reduced temperature, could depend on the amount of tests performed. Maybe, if there were a larger amount of tests the results would not differ at all. However, the results were even amongst the ones of the same kind and will therefore be stated as valid.

It was discussed whether all of the adhesives were going to work, due to all of them being stronger than the requested force ($270N$ or $0.13\ MPa$). However, the two weakest ones were removed and the rest were evaluated depending on other requests, such as cost and environmental issues. From this, L2 and L5 were chosen to be the best fit for the application of the project. It is possible to believe that the other two, the ones that did well in the tests but failed during selection, might also work.

It was hard to decide which two adhesives that were going to continue in the tests after the first phase. In the beginning of the project, it was believed that the adhesive that was stronger than the SMC would be the best choice. However, more parameters played a role in this selection. The first reason that L2 and L5 were the ones to continue were that they, except for giving a good performance in the test, also were easy to handle, cheap, health and environmental friendly and easy to applicate, see Table 2 in *appendices*. Another reason for choosing L2 and L5 was their structure, one being an epoxy and the other a cyanoacrylate. It was believed to be fair to costumers to have different options, not only one defined type of adhesive.

And about the Table 2: The parameters were all set up as relative to the other adhesives. It was a scale from one to six where the "best" adhesives in each category got one point and the "worst" got six point. The adhesive with the lowest score was considered the best overall. However, three adhesives got almost the same score but one got a fairly higher, making that one, L1, a poor candidate for further investigation.

Concerning the cost parameter, the cost was calculated as the cost of a small batch divided in volume of cartridge and then set in relation in the one to six scale. However, it might have been more fair to calculate how much glue was used for every test, since there tended to be consumed a lot more epoxy than cyanoacrylate. But for this test it was important to fill out every part of the joining surfaces which was provided by pressure and rotation, which made the adhesive come out on the sides, making the usage calculations difficult.

One could also think that the SURF failure was a bad thing for the results. However, the SURF failure occurred at a stress level almost as high, (or higher), than the one for the SMC failure, meaning that it was not important, and should be seen as a regular SMC failure. The results showed that one could not foresee if it was going to be a SMC- or a SURF failure, due to the high stress level.

However, when an adhesive failure occurred the results were irregular and unpredictable. Sometimes the failure occurred during fastening, showing minimum force resistance. For these two adhesives, it was clear that they were not going to work. The failures occurred on both the SMC and the aluminum, meaning that it was not only the surface treatment of the SMC but also the one of the Aluminum causing the failure. The two adhesives might work if other surface treatments are considered.

4.2.1 **Rotation**

The rotation calculations showed that the shear stress in the adhesive, underneath the magnet, is about one percent out of what the adhesive can take, however, during the rest of the project it can be seen that a data sheet is not always reliable. Maybe there should be done some rotation tests, just to validate the accuracy of the data sheet.

4.2.2 **Die- and Punch Tests**

For the die- and punch tests, the joining surface was calculated as a rectangle even though the real area had a curved edge from the diameter of the aluminum cylinder, this might have distorted the results. However, the placement of the component was not as precise either, since the component was placed by hand. It would have been better to have a bigger component or an aluminum fixture created to fit the component.

4.2.3 **Adhesive Maximum**

It was odd that the adhesive maximum tests showed that the Permabond 820 should hold for less than it did when applying it to aluminum and SMC. However, it might be that the adhesive reacted with the SMC in some way, creating a stronger bond. It could also be that that single test, L5 joining aluminum to aluminum, was a poor test. Maybe something happened that made the test different, from the rest. The only way to know should be to do another test, under the correct circumstances, to see if there could be a different result. During the project, it was decided not to do a second test, due to time aspects and material use, but perhaps the possibility may occur in further investigations. However, the safety data sheet did not mention any shear or tensile stress level when applied to aluminum, maybe the adhesive was not meant for that.

The Permabond ES550 on the other hand, did way better than the safety data sheet. The adhesive had no problem holding the aluminum cylinders together. It is possible that changing temperature in the oven, during cure, affected the epoxy to reach higher strengths since not all ovens act the same. It is hard to say if the oven was providing the exact same temperature and environment during the whole cure time. It could also be that the safety data sheet was written with some safety margin.

4.3 Crimp Tests

A major problem with the crimp test process was deciding for a diametrical grip. The diameter of the fixture had to be calculated and measured to be sure of the grip. However, the calculations were wrong sometimes and the problem was the grip itself, not being clear if it was diametrical or radially. There were also discussions about the safety factor and if the tests should have bigger or smaller grip than normal. It ended up being ten times bigger than the recommended value, creating bigger stress levels in the materials. Nevertheless, it was seen from calculations that the recommended value would not have worked, the construction would not have been able to take the force level with a grip of only 12 um.

The oven did not go all the way up to 250 degrees, it stopped at 237. However, the stator was still able to slide through proving that the process would work at a lower heating. Furthermore, if the stator can slide in at a lower temperature, it might also slide out at a lower temperature.

Concerning the stators not being totally round, but a bit oval, it was decided that they were going to represent the real situation in a good way, since all of the stators were pressed in the same way. The test would not have been fair if the test stators were round and the real stators were oval.

It was then hard to tell what force that was the important one. The stators placed in the middle of the aluminum housing had to slide on the inside to be able to fall out. It was decided that it would be the first force disturbance that represented the actual failure, and not the force that made the stator fall out of the housing. This created an averge of a force ten times higher than the requested one. However, the construction itself was not that similar to the one that *Höganäs* is thinking about using for this application. The outer diameter of the aluminum housing was created as a standard measurement to make manufacturing easier; maybe it should have been smaller to create a more authentic construction.

The tests should also been made in elevated temperature to be able to state if the constructions will function when the engine gets hot. It is possible to believe that the stator would fall out if the engine is heated.

4.4 Clamping

Even though the calculations were highly simplified, they were thought to represent the actual case in a fair way due to the simple attachment. However, the shear strength turned out to be a fourth of the maximum allowed by the data sheet. The area calculation itself was a bit tricky and should not be taken too seriously, it might need modifications. However, it was seen in the crimp tests that a construction like this, held up by supports in the ends, are able to hold for the small force of $F = 270\ N$.

The used diameter was $d = 65\ mm$, not taken into consideration the variations of the components. The components have tolerances within $d = 64{,}999$ to $d = 65{,}005$, (as can be seen in the chapter about the *Test Components*). Since the difference in diameter was so small, while adding the new required area, it is possible to think that there should be more of a safety factor, to make sure that the step would actually grip the edge, even if the stator hade another measurement than $d = 65\ mm$ straight. A safety factor would mean a bigger diameter, and by that a bigger area.

5 Conclusions

From the investigation, carried out at Häganäs AB in cooperation with the Materials Engineering at Lund University, it can be concluded that:

Gluing can be used as an attachment method for joining Somaloy® and aluminum in mechanical constructions such as an electric motor. There were two adhesives to make it through the investigation.

The epoxy, *Permabond ES550*, performed perfectly in almost every test and the average stress level was more than 20 times higher than the requested.

The cyanoacrylate, *Permabond 820*, did well when tested in lower temperatures but was affected by the heat in the elevated temperature tests.

It is not to recommend to use *Permabond 820* for this application even though the stress level was more than ten times higher than the requested.

Sinter chamfer turned out to be highly important. When the edge on the test components was removed the adhesive got contact with the entire surface, which was not the case when the edge was still on. This did not apply for the *Permabond ES550*, since the epoxy is much thicker it will fill up every gap.

Crimping is a simple method that can be used for attaching the components. The tests made showed that it was easy to place the stator in the heated aluminum housing and a construction, such as this, will hold for a force ten times higher than requested.

It is hard to tell if clamping is going to work, due to the limited effort put in investigating this area. However, the calculations showed that the stator would need an extra edge of 0,02 mm all around to be able to hold for the requested force.

6 Further investigations

It could be interesting to see if the test where *Permabond 820* was applied to only aluminum was an accurate test. Maybe this could be further investigated to get a broader understanding of the adhesive and its actual abilities.

It would also be interesting to see how the rest of *Höganäs'* materials would do in the tests. It is possible that an other material would be used for the rotor and stator.

The crimp tests needs a further investigation to be able to see if it is possible to use the method inside the engine, due to temperature differences. It also needs to be tested with a more authentic construction.

7 Appendix

The chapter will show the raw data, such as tables and tensile test results.

Table 2: showing the evaluation of the six adhesives. 1 being the best and 6 being the worst.

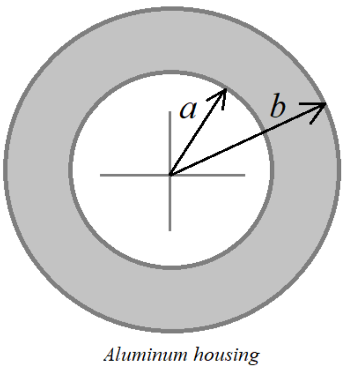
	type	1P grinded	5P grinded	1P ruff	5P ruff	score*	curing time	curing temp	curing*	cost**	ease of use*	environmental***	total score
Loctite 648	anaerobic acrylat	3,3	6,6	3,3	6,3	4	2h	22	4	6	6	5	25
Permabond ES550	epoxy	3,4	6,2	3,4	6,7	3	1h	150	2	1	1	6	13
Permabond ES562	epoxy	3,3	6,8	1,7	3,6	5	1h	130	1	3	3	4	16
Araldite AV4600	epoxy	3,6	6,7	3,1	7	2	1h	180	3	2	4	3	14
Permabond 820	cyanoakrylat	3,1	7,2	3,3	7,2	1	24h	22	5	5	2	1	14
Permabond HH131	anaerobic threadlocker	2	2,3	1,9	3,8	6	24h	22	6	4	5	2	23

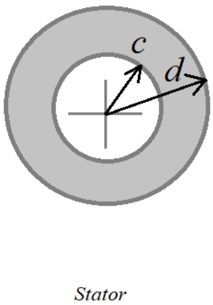
***Relative to one and other.**
****SEK/ml, small batch and relative to one and other.**
*****Concerning the safety data sheets and the number of contents listed on the “restricted list” [14].**

7.1 Calculations

7.1.1 **Crimping**

$F = 270\ N$	The axial force required (from the magnets)
Δd	Radial grip: the difference between a and b
p	Pressure on the stator component caused by crimping
$a = 64{,}6794\ mm$	Inner diameter of the aluminum housing before the test
$b = 125\ mm$	Outer diameter of the aluminum housing
$c = 39\ mm$	Inner diameter of the stator
$d = 64{,}999\ mm$	The minimum outer diameter of all stators
$d_2 = 65{,}005\ mm$	The maximum outer diameter of all stators
$L = 3\ mm$	The length of the edge of the stator
$\mu = 0{,}18$	Coefficient of fiction [23]
$E_{stator} = 150\ GPa$	Young's modulus of the stator [24]
$E_{housing} = 70\ GPa$	Young's modulus of the aluminum housing [23]
$v_{stator} = 0{,}23$	Poisson's ratio for the stator [24]
$v_{housing} = 0{,}34$	Poisson's ratio for the aluminum housing [23]
$e = b = 64{,}999\ mm$	Inner diameter of the housing after the test





$$p = \frac{\Delta d}{2(\frac{a}{E_{housing}}\left(\frac{a^2 + b^2}{a^2 - b^2} + v_{housing}\right) + \frac{d}{E_{stator}}\left(\frac{d^2 + c^2}{d^2 - c^2} - v_{stator}\right))}$$

$$p = \frac{F}{\pi\ 2d\ L\ \mu}$$

$D = 64{,}8794\ mm$ Inner diameter of the aluminum housing

$\alpha = 0{,}000023\ C^{-1}$ Coefficient of thermal expansion [23]

$\Delta T = 230\ C$ Temperature difference (20° → 250°)

The diameter of the housing after heating would be:

$D_{new} = D * \alpha * \Delta T$

$D_{new} = 65{,}2226\ mm$ The diameter of the aluminum housing after heating.

7.1.2 **Rotations:**

$m = 5\ g$ Mass of a magnet

$w = 4000\ rpm$ Angular velocity of the rotor

$$\frac{2\pi\ 4000}{60}\ \frac{rad}{s} = 418\ \frac{rad}{s}$$

7.1.3 **Clamping:**

$\sigma = 110\ MPa$ Yield strength of the stator

$F = 270\ N$ Force of the magnets

$$A_{stator} = \pi\ (\left(\frac{d_y}{2}\right)^2 - \left(\frac{d_i}{2}\right)^2)$$

$$\sigma = \frac{F}{A}$$

$$=> A_{req} = \frac{F}{\sigma}$$

$$A_{new} = A_{stator} + A_{req}$$

$$A_{new} = \pi(\frac{d_{new}}{2})^2$$

$$=> d_{new} = 2\sqrt{\frac{A_{new}}{\pi}}$$

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