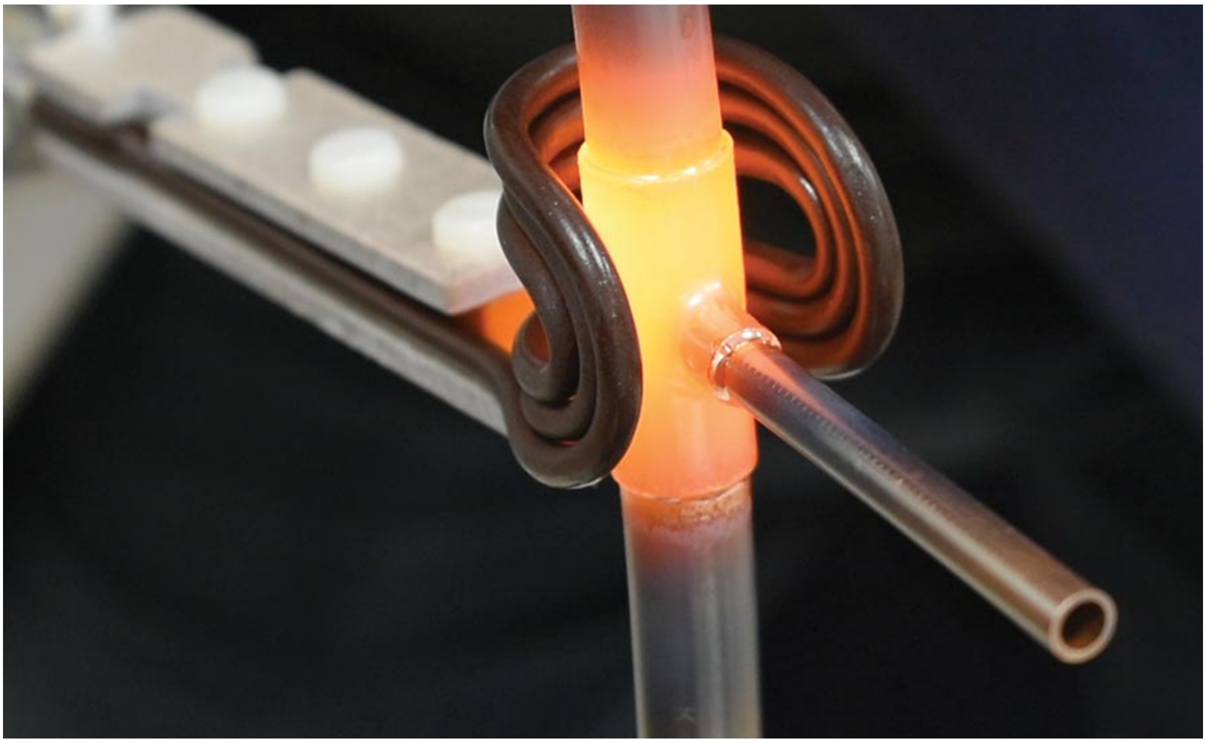

Investigation of induction brazing on circular pipes

A detailed investigation of an induction brazing process

Master’s thesis at Master Program Production Engineering

Anton Wretström

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
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MASTER'S THESIS 2022

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Supervisor: Johan Ahlström, Department of Industrial and Materials Science
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Master's Thesis 2022
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Induction brazing.
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Abstract

This master's thesis was done at the department of Industrial and Materials Science at Chalmers University of Technology in Gothenburg. A company with relating interests initiated the project, and helped with setup and experiments. They have required to remain anonymous, and are referred to as "the company" in this report. Some withdrawal of details are done to protect their business case.

This thesis project was an investigation of induction brazing on circular pipes and a detailed investigation of an induction brazing process station. The background for the project was problems with not fulfilling quality requirements for induction brazed joints at a specific induction brazing station. The different quality defects were the presence of voids and other non-metallic inclusion inside the joints. The purpose of the project was to identify the main influencing parameters for the unfulfilled quality requirements. The investigation was done by a combination of a theoretical study and an experimental study. The theoretical study was carried out to understand the fundamentals of brazing and potential influential parameters for a brazing process. At the experimental part of the project, the influence of different parameters were investigated. Different induction machine programs were used in combination with different filler materials tested. The way and the amount the flux was applied was examined, and how different surface preparations affect the quality of the induction brazed joints. The manual flame brazing of the same joints was set as a reference for the results.

Combining the theory from the theoretical study and the examined parameters in the experimental part, conclusions could be drawn that the main quality issue most likely is that the gaps are too big for the joints. The current design of the joints is adjusted to manual flame brazing that provides joints with high-quality joints. However, when it comes to induction brazing smaller gaps are required to achieve sound joints. Proposed solutions were based on reducing the gaps for the investigated joints. Reduced gaps will, according to the theory, increase the capillary flow of the filler material during the brazing operation. In combination with smaller gaps and better flow, the risk for voids and other inclusions will probably be reduced. Another influencing process parameter discovered through the project was the lack of centering of the pipes in the connections. Proposed solutions related to the lack of centering were based on chamfers in the joint design of the pipe connections.

Keywords: *Brazing*, *Induction brazing*, *Metallurgical bonds*, *Filler materials*, *Flux*, *Circular pipes*, *Copper*, *Stainless steel*

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I'm also beyond grateful to Fredrik for the excellent X-ray reports and other excellent inputs to this project. You always took your time to answer my endless emails, which is greatly appreciated. Cheers to Sinisa, Sebastian and Alexander for your help during the experimental tests and knowledge in brazing. Without you, the test could not be performed. I also want to thank Jim for providing me with products for the experiments, even with short notice. Further, a thank you to everyone else who has helped me at the company.

I also want to thank Richard, Mats, Kari, Jari, and Kjetil for providing me with information of great importance for this master's thesis and excellent guidance along the way. Thank you Emelie for being my opponent and for the great help with the report of this master's thesis.

At last, I want to thank my family with great hugs for the support along the way when it has been hard and that just you are my family. Thank you for the help with the compilation of the master's thesis report. In conclusion, I would like to say that this work has been a work that has involved a great deal of responsibility and difficulty, but personally, it is the most fun experience I have done that is related to work and school.

Thank you!

Anton Wretström, Gothenburg, 18 March 2022

Contents

List of Figures

List of Tables

1

Introduction

This master's thesis was done at the department of *Industrial and Material Science* (IMS) at *Chalmers University of Technology* and with Johan Ahlström as supervisor and examiner from IMS. A company with relating interests initiated the project, and helped with setup and experiments. They have required to remain anonymous, and are referred to as "the company" in this report. Some withdrawal of details are done to protect their business case, but the research methods and analysis of the results are presented in sufficient detail to judge the academic performance.

The project was performed in a time frame of about 20 weeks, starting 1^{th} of November 2021. Due to secrecy at the company, two versions of the report have been made and some information is concealed. One version was e-published at Chalmers university of technology's *Open Digital Repository Student Theses Database*, and another non-disclosed version of the report was distributed and presented internally at the company.

1.1 Background

The product at the company that was in focus in this master's thesis project included connections where two pipes (one ordinary pipe and a fitting pipe) of different materials were joined together in an induction brazing station at a temperature above $450°C$. Some of the connections produced by the automatic induction brazing station did not fulfill the quality requirements when they was examined by X-ray equipment. The quality problems of the joint include among others:

- Visual appearance.
- Joint filling.
- Inclusions and voids inside the joint.

The pipes contain fluids in the final product. Therefore, problems like leakage and loss of fluids may result in loss of performance and a negative environmental impact. However, the unfulfilled quality requirements have not only led to problems with the product itself but also shut down the station and the brazing is carried out manually to ensure high quality of the joint. This is both more expensive and leads to lower productivity.

1.2 Purpose

The purpose of the master's thesis is to execute a deep investigation of the automatic station where the induction brazing is performed. This will mainly be accomplished with different tests and a detailed literature study. The investigation will examine the induction brazing process and the production- and material parameters to find the main influencing parameters for the unfulfilled quality requirements. Further, the aim is to present one or more possible solutions to the problem and investigate the possibility of recommending a solution within the delimitations described below.

1.2.1 Clarification of the research questions of the thesis

Questions that will be answered by the master's thesis project are:

Research question 1: Which are the main affecting parameters causing the unfilled quality requirement of the joint?

Research question 2: Which different solutions could possibly help meeting the quality requirements?

1.3 Delimitations

Delimitations that will be applied to the master thesis project are:

- **Performed tests of the induction brazing process is limited to the test equipment available at the company.** If necessary, further estimation can be made through a literature study.

- **No cost calculations of the different solutions will be performed.** The thesis will only present the most optimal solution for the brazing process.

- **Final solution(s) and recommendation(s) do not need to be tested.** If time is short, the result of the final solution(s) can be estimated by a literature study.

- **The focus of the final solution(s) will firstly be to use the solution(s) available at the company.** The reason is to limit the scope.

- **The time frame for the master's thesis is about 20 weeks.** If the thesis project is not finished or presented before 20^{th} of March 2022, there is a possibility to extend the time to no longer than 30^{th} of April 2022.

1.4 Description of brazing process at the company

The type of joining method used at the company is induction brazing, with a brazing temperature over $450°C$ during the process. The filler material is manually placed on the connection before the brazing process, see Figure 1.1. Regarding the shape of the joined parts, it is a column/gap brazing process where the surfaces of the base materials (that will be joined to each other) are parallel to each other with a gap between, called a brazing gap. The filler material is heated by coils through induction heating and then melted. The melted filler material will then flow into the gap of the joint with the help of capillary forces (Björklund et al., 2015). Protection gas is used inside the pipes to protect inside from oxide formations and flux is brushed on the joint before the induction process to protect the outer surface of the pipes from oxide formation. The pipe was made of copper with a fitting pipe of stainless steel. The used filler material was silver-based and the flux was a fluoride-borate salt-mixture paste.

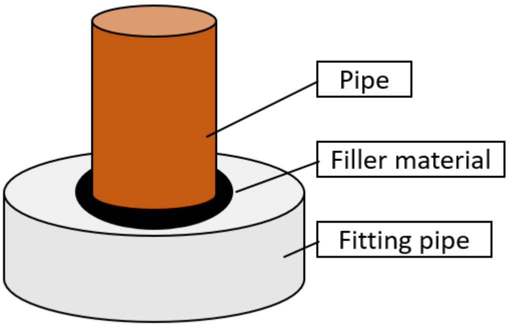

Figure 1.1: Illustration of a connection between a pipe and fitting pipe with pre-placed filler material.

2

Theoretical framework

This chapter describes the theoretical framework and influencing parameters of brazing. Additionally, the principles for induction heating and different parameters affecting the induction brazing process are investigated. The chapter ends with a description of possible defects in brazed joints and inspection methods for brazed joints.

2.1 Brazing

Brazing is a joining method where the surface of two or more base-metal workpieces is joined together by melting a fusible metal alloy, called filler material. The basic idea is to use a filler material with a lower melting temperature than the metal workpieces to keep the workpieces in a solid-state. The same method is used for the similar joining method *soldering*. However, the difference between the two methods is the working temperature which is above $450°C$ for brazing and below $450°C$ for soldering. Different types of flux are also often used to clean and prevent oxidation on the surfaces of the base metals to facilitate the flow of filler material (Björklund et al., 2015).

2.1.1 The mechanics of the brazing process

The brazing process can be described in four main steps
(Jacobson and Humpston, 2005):

1. Both base-metal parts and the filler material are heated to at least $450\ °C$ in the region of the joint.
2. The region is further heated to the temperature where the filler material melts. However, it is important that the base material is still in solid phase.
3. The filler material is placed at the joint either by pre-placing or added by hand and held in place by surface tension. The molten filler material is then spread into the joint by capillary forces. Here the filler material wets the surfaces of the base-metal workpieces.
4. The heat source is then turned off and the joint solidifies. The filler material that has spread into the joint is fixed to the base-material work pieces through metallurgical bonds and atomic bonding, further described in Section 2.1.2.

2.1.2 Formation of metallurgical bonds

If the surfaces of the base materials are sufficiently clean from oxides and dirt, the molten filler material can wet the surfaces of base materials during the brazing process. An allegation between the base- and filler materials can then occur in a narrow zone. By diffusion, a metallic unit is then created in this zone (Björklund et al., 2015). Diffusion is a phenomenon occurring when atoms in the crystal structure of the metal move to another place in the structure. This is due to metals naturally having a lack of atoms in some places in the crystal lattice, creating a movement of the atoms. Nearby atoms to the empty space then moves to fill in the hole, but are itself leaving an empty hole in the lattice. This creates constant movement and the rate of the movement increases with temperature. The driving force is Gibbs's free energy striving to even out any concentration difference in the crystal lattice. The direction of the movements is random. Additionally, other types of diffusion are much faster than the movement in the crystal structure: surface diffusion and grain boundary diffusion. All these three types of diffusion (crystal-, surface- and grain boundary diffusion) are dependent on temperature and time (Leijon, 2014) and are illustrated in Figure 2.1.

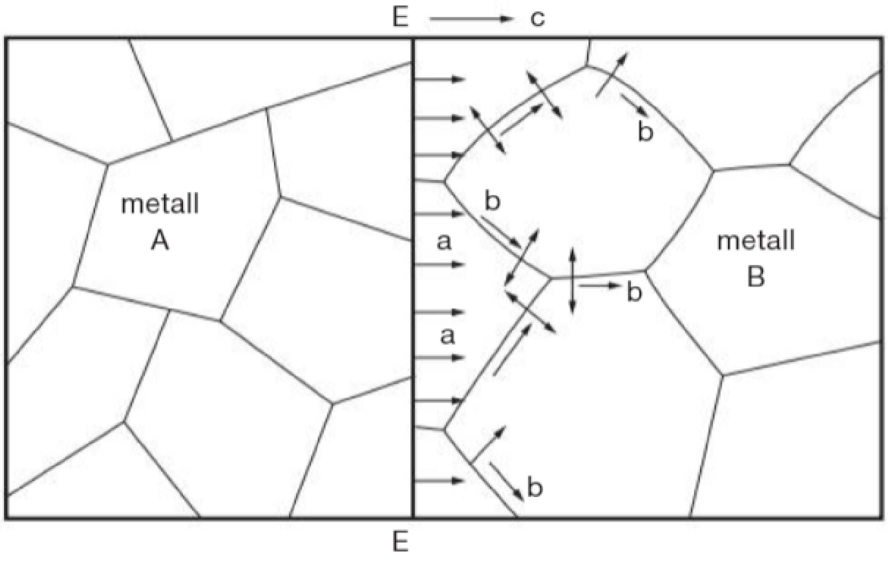

Figure 2.1: The three types of diffusion between two metals: a) Diffusion through the crystal structure, b) Diffusion through grain boundary, c) Diffusion through the surface. From the book *Karlebo Materiallära* (Leijon, 2014), (s. 30), by Willey Leijon, 2014, Stockholm: Liber AB. Copyright 2016 by Liber AB. *Used with written permission.*

During the brazing process, the filler material melts and flows down the gap where the diffusion between the base- and filler material occurs. A metallic unit is then created, visualized in Figure 2.2.

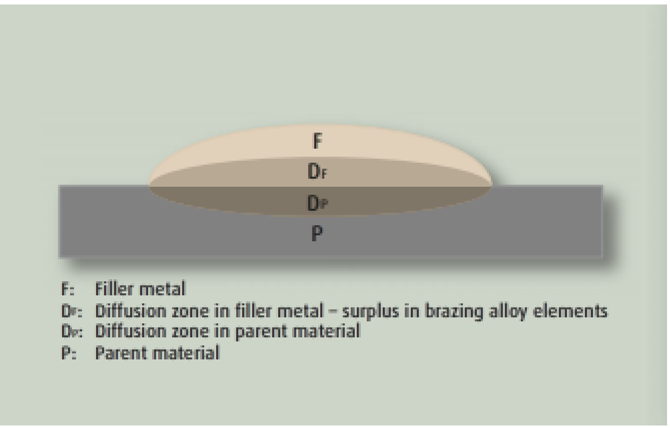

Figure 2.2: Illustration of the diffusion zones between the filler material and the base material. From the source *Principles of brazing and Soldering: Joining Technology* (Schnee and Materials, 2019), (s.11), by Schnee and SAXONIA Technical Materials, 2019.
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2.2 Influential parameters of brazing

Parameters that affect the process of brazing are (Jacobson and Humpston, 2005):

- Characterisation of the base materials.
- Characterisation of the filler material.
- Flow of the filler material.
- Design of the joint and gap.
- Surface preparations.
- Temperature and time.
- Heating source.

Each of the parameters will be further described in Section 2.2.1 to 2.2.7.

2.2.1 Characterisation of the base materials

The base materials have a considerable role in the final strength. Base materials with higher strength properties produce joints with higher strength than base materials with lower strength properties. Other influencing factors are the production and processes method of the materials since heating causes residual stresses during cooling (Jacobson and Humpston, 2005).

When choosing the base material for the joint, consideration of the thermal expansion is of importance since different materials have different coefficients of thermal expansion. When heated during the brazing process, the materials will expand differently which will either close or open the gap of the joint. Gaps will be further described in Section 2.2.5. The thermal expansion also affects the gap when the joint is cooled down and the filler material has solidified. When cooled down, the material contracts (shrinks) and different coefficients of thermal expansion in the materials can create residual stresses during the solidification and affect the final properties of the joint (Jacobson and Humpston, 2005).

During the manufacturing processes of soldering, brazing, and welding, high temperatures are involved and the heat generated in the material flows within the material. This flow of heat strongly affects the output of the manufacturing process. The heat flow is dependent on the properties of the base materials and if the base materials are made of two different materials, they will have different physical properties such as heat capacity, heat conduction, and density (Das et al., 2021).

Thermal conduction means the material's ability to conduct heat. When a part of the metal is exposed to heat from a heat source, the heat will flow to other parts of the metal and the driving force of the thermal conduction is to equalize the temperature differences. The heat capacity of a material is defined as the amount of thermal energy that is needed to raise the temperature one degree in the scale of Kelvin. Materials with high specific heat capacity require more energy to increase the temperature than a material with low specific heat capacity. Further, density is defined as the mass of the material per unit of volume. Density is dependent on temperature since the materials available will expand in volume during a temperature rise (Tritt, 2004) (Das et al., 2021).

The different properties mentioned will affect the heat cycle in the materials during the brazing process. When the base materials are in a molten state and joined through brazing, they will form a metallurgical bond, described in Section 2.1.2. When the different materials have formed a metallurgical bond the materials will be connected, which allows heat to be distributed between the materials. Materials with higher heat capacity and higher thermal conductivity will act as a heat sink for the connected parts and the heat will be drawn to the material. This will affect the heat cycle and the output of the manufacturing process.

Other influential parameters affecting the joint related to the base material are (Jacobson and Humpston, 2005):

- The alloying of the base material.
- Oxide stability of the base material.
- Precipitation of carbide for the base material.

This master's thesis will focus on copper and stainless steel as base materials. The materials have different material properties. Copper has higher thermal conductivity than stainless steel and during the induction brazing process, the heat flow will be faster in the copper part than in the stainless steel part. Copper also has lower specific heat than stainless steel, meaning that a segment of the copper will reach the working temperature of the brazing process faster than a segment of the stainless steel part in the same region. When it comes to thermal expansion, copper and stainless steel have similar values and the gap between the parts will not be appreciably affected when reaching the working temperature. Data for the properties of the base material used can be seen in Table 3.1 in Chapter 3.

2.2.2 Characterisation of the filler material

The filler material is used to fill the gap in the brazing process. There are four main types of filler materials, divided by the working temperature range (Roberts, 2013):

1. Working temperature between 450°C and 600°C.
2. Working temperature between 600°C and 850°C.
3. Working temperature between 850°C and 900°C.
4. Working temperature over 900°C.

The filler materials can also be divided in different classes depending on their material composition, stated in Table 2.1 (Roberts, 2013).

Table 2.1: Different classes of filler materials depending on their material composition.

Class:	**Mainly consisting of:**
Al	Aluminium and Magnesium
Au	Gold
Ag	Silver
Cu	Copper
CuP	Copper and Phosphorus
Ni	Nickel and Cobalt
Cu-Sn-Ni-P	Unclassified copper-tin-nickel-phosphorus group

Filler materials are often a composition of different alloys to get the right properties for the brazing process and the desired joint. Unlike pure metals with a distinct melting temperature, filler materials have, like alloys, a melting temperature range called working temperature. The working temperature includes two types of temperature points (AWS, 2007):

- Solidus - the temperature where the filler starts to melt, depeding on alloy.
- Liquidus - the temperature where all including alloys in the filler materials are melted and the filler material is completely liquid.

Between the melting temperature points, the alloys can be in different states (solid or liquid). This can make the filler material "sluggish" in the working temperature due to not yet liquefied material, which in turn can affect the flow and viscosity of the filler material (AWS, 2007). Viscosity is a property for fluid and liquefied metals related to the transport of the fluid. A higher value of the viscosity will, in everyday speech, lead to a ”thicker” fluid (NE, 2022). The viscosity is dependent on temperature, pressure, and concentration of certain alloys included in the liquefied metal (Echendu et al., 2011). Echendu et al (2011) made a theoretical investigation of the viscosity of some liquid metals and alloys. Some of the results from the investigation can be seen in Figures 2.3 and 2.4. Figure 2.3 clearly illustrates that viscosity is affected by temperature and in Figure 2.4 it is visualized that a higher (or lower) concentration of silver in a copper and silver alloy will affect the viscosity (Echendu et al., 2011).

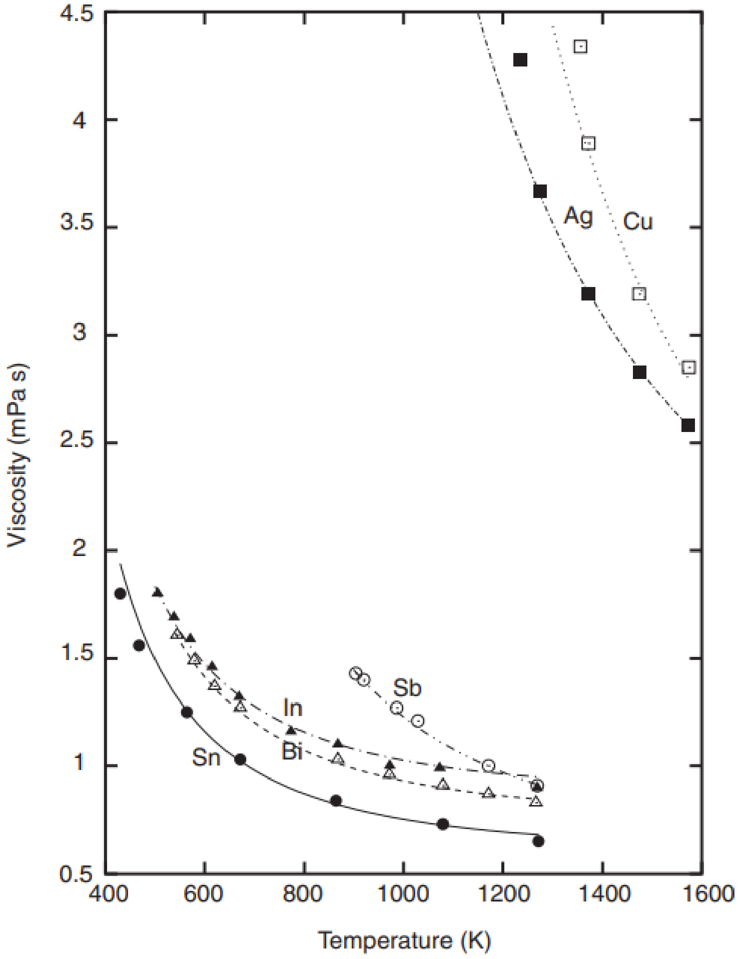

Figure 2.3: Viscosity for some liquefied metals dependent on temperature. From the article *Theoretical investigation of the viscosity of some liquid metals and alloys* (Echendu et al., 2011), (s.251), by Echendu et al., 2011.
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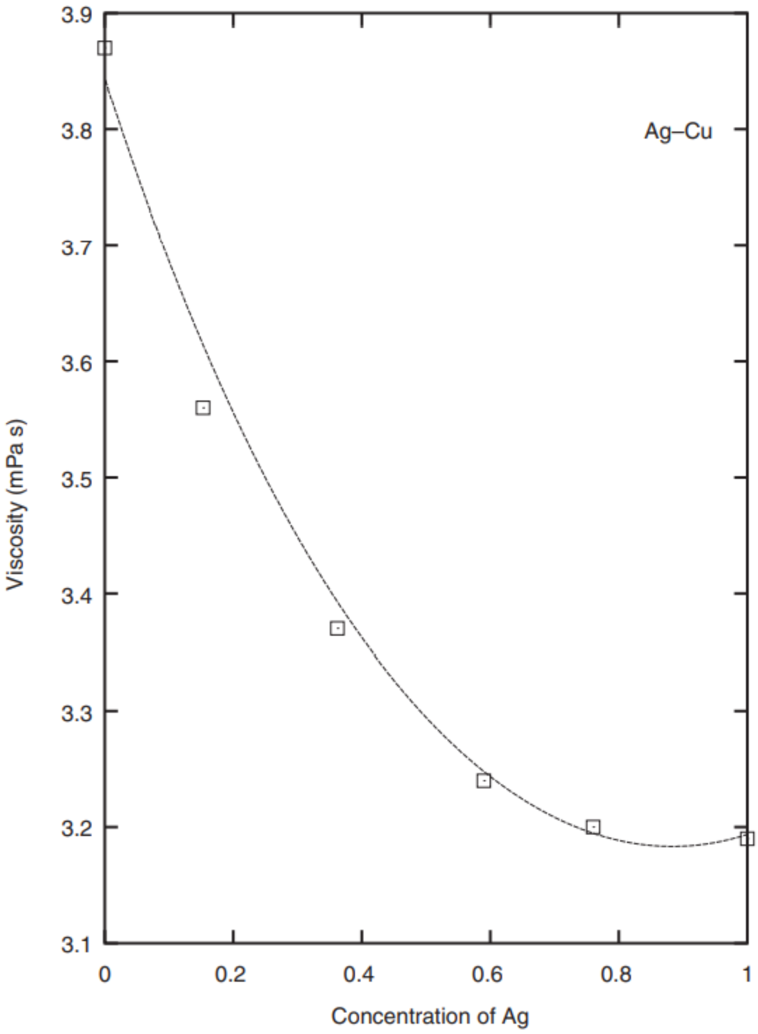

Figure 2.4: Viscosity for a liquefied alloy (copper-silver) dependent on the concentration of silver. From the article *Theoretical investigation of the viscosity of some liquid metals and alloys* (Echendu et al., 2011), (s.254), by Echendu et al., 2011. *Used with written permission.*

The viscosity affects the formation of small gas bubbles and other non-metallic inclosures in the solidified joint, which can be seen as defects in the brazed joint (Echendu et al., 2011). The lower viscosity of the filler material can theoretically be achieved with increased working temperature (Sekulić, 2013) and is favorable for the flow of the filler material described in Section 2.2.3 since it will decrease the surface tension. Further, the filler material will itself have a better flow and spread better compared to filler materials with higher viscosity. The superior flow will better remove impurities, gas bubbles and other voids to create a more compact joint. The lowered surface tension will also allow gas bubbles and other inclusions to escape the brazed joint during the liquefied phase (Rossmann, 2022).

Other important characterisations of the filler material are (Jacobson and Humpston, 2005):

- Sufficiently capillary flow of the filler material at the working temperature of the brazing process to provide a proper filled joint.
- Proper ability of the filler material to wet the surfaces of the base materials.
- It is important that the filler materials with a high melting range are stable during the brazing process to avoid premature release of elements with a lower melting point than the liquidus point of the filler material.
- Proper ability of the filler material to form a metallurgical bond with the base material.
- Knowledge of possible erosion process between the filler material and base material when the materials are joined.
- During the working temperature to have low volatilizing characteristics. Volatilization means a transition from the liquid state to the gas state, in this case, that the alloying elements of filler material turn to gas state from a liquid state.

Filler materials can come in a variety of shapes and forms, depending on the application for the brazing process. The most common are rod, wire, and pre-forms. Rods are used when the brazing process is done manually on simple assemblies during the heating process. The advantages of rods are that they are cheap to manufacture and can be ordered in different dimensions (thickness and length). Wires can be used with a mechanical wire feeder and are therefore more useful in automatic brazing processes. Pre-forms can be shaped in different forms, where rings are most common. The pre-forms are placed at the brazing assembly before the heating process, making them suitable for automatic processes like induction brazing. Pre-forms have some advantages but also some disadvantages described below (AWS, 2007).

Advantages with pre-forms (AWS, 2007):

- Consistent amount of filler material is placed every time at the joint and the amount of filler material is independent of the operator.
- A certain amount is applied for each pre-form. In this way, excess flow of the filler material can be avoided.
- Makes the brazing process more simple with fewer operations included.

Disadvantages with pre-forms (AWS, 2007):

- More complicated manufacturing resulting in higher costs.
- The fit of the pre-forms on parts of the brazing assembly is dependent on the tolerances, but also on the manufacturing of the pre-forms.
- A more simple process can result in sloppiness from the operators placing the pre-forms on the brazing assembly, which can create misplacement of the pre-forms and reduce the effectiveness.

Unlike ordinary solid filler materials, there are filler materials with integrated flux, meaning that flux powder is either placed inside the filler material or coated on the filler. This is achieved by different manufacturing methods (Sharma et al., 2021). Flux is further described in Section 2.2.4. Some of the defects that can be seen when manually applying flux to ordinary solid filler material are entrapped inclusions of flux residues in the joint. The reason for this can either be too much flux applied or that the flux is applied in the wrong way. This can lead to the creation of voids and porous brazed joints (AWS, 2007). Flux integrated filler materials can be a possible solution due to the consistent application of flux (inside the filler material) giving constant quality and less probability of entrapped flux. However, flux integrated filler material will not eliminate the problem with entrapped flux, but a successfully adapted flux integrated filler material can give good results. This can be seen in Figure 2.5, where solid filler material combined with manually applied filler material were compared with flux integrated filler material for a special application. The figure visualizes the better results when using flux integrated filler materials for the specific application (Meltolit, 2022).

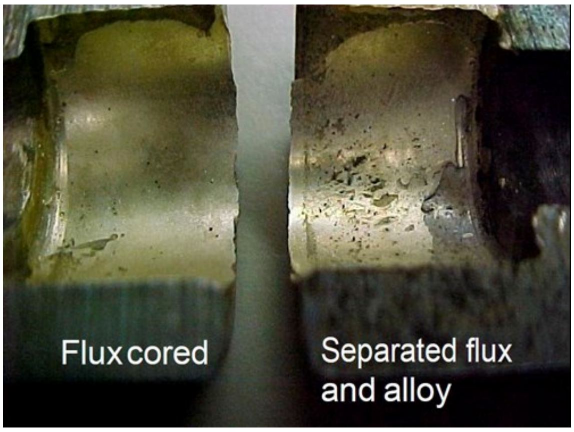

Figure 2.5: Comparison between the brazing results between use of solid filler material + flux manually applied and flux integrated filler material for this special application. From (Meltolit, 2022), by Meltolit, 2021. *Used with written permission.*

Integrated flux in the filler material has some other advantages (Meltolit, 2022):

- Simplifies the manufacturing process with less operations.
- Less mass needs to be heated compared to solid filler material, resulting in a shorter process time. Additionally, the base material will be less affected due to lower heat energy exposure.
- About 20 % less amount of material needs to be used compared to solid filler material.
- Up to 10 times less flux remains at the application after the brazing process compared with using solid filler material with manually applied flux. This simplifies the cleaning process afterward.

This master's thesis project will have its focus on the class Ag (silver) brazing filler material in the melting range of $600°C$ to $850°C$. Both solid and flux-integrated silver-based filler materials will be used. Some of the characteristics of filler materials with silver as a base are that the higher amount (weight percent) of silver the lower the working temperature and at the same time the higher flow-ability (Meltolit, 2022). Silver in the filler material also positively affects the corrosion resistance and contributes to the good aesthetic color of the joints, suitable for stainless steel as a base material for example. Filler materials based on silver are often compounded together with copper. The mix of silver and copper has poor wetting characteristics on ferrous-based materials, like stainless steel. Small amounts of zinc and tin will exhibit enhanced wetting on ferrous base materials. The tin approves the flowing characteristics and the zinc lowers the melting temperatures of the silver-based filler material (AWS, 2007) (Schwartz, 2005). Data for the properties of the base materials used can be seen in Table 3.2 in Chapter 3.

2.2.3 Flow of the filler material

The flow of the filler material is affected by the wetting of the joint. The phenomenon *wetting*, is when a filler material (a metal in liquid state) spreads in a thin layer and adheres to the surface in the joint gap (capillary) between the surfaces of the base materials. The driving force of the flow is capillary action. The capillary action is a combination of the force of attraction of the liquefied filler material to the surface of the base material (adhesion), and in combination of the energy from phase transformation during the diffusion process between the filler material and base material. The wetting conditions enable further flow of the filler material into the gap and the wetting of the joint is also necessary to enable contact angle between filler and base material, see Figure 2.6. The lower the angle is, the better the wetting of the joint. This is necessary to be able to create decent joints. In other words, the degree of wetting has a major impact on the properties of the brazed joint (AWS, 2007).

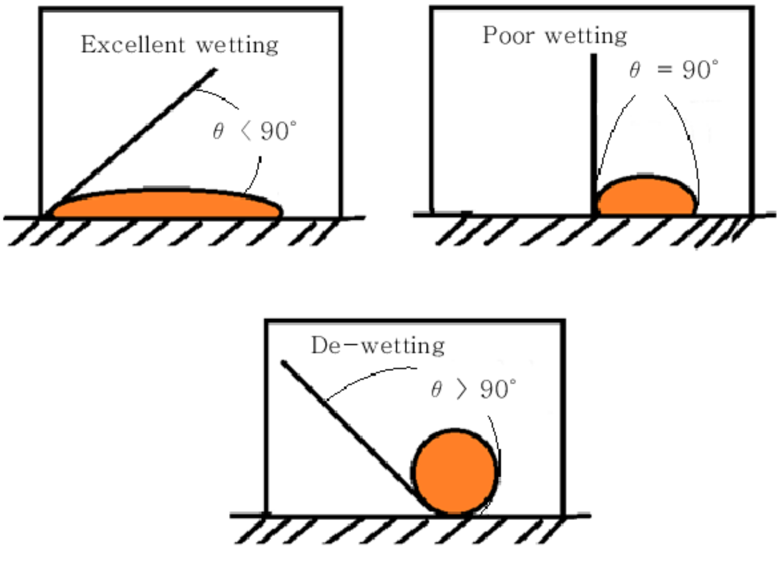

Figure 2.6: Illustration of contact angle between the filler and base material. From the article *Effect of Various Factors on the Brazed Joint Properties in Al Brazing Technology* (Sharma et al., 2016), (s.31), by Sharma et al., 2016. *Used with written permission.*

Good wetting of the joints is also necessary to get a smooth, continuous, and rapid flow of the filler material down the joint gap. The flow must be rapid enough to be able to fill the joint gap before the heated section reaches the melting temperature of the filler material. Wetting is also necessary to create enough capillary action to draw all filler material down in the joint (Jacobson and Humpston, 2005), visualised in Figure 2.7. Wetting is strongly dependent on the design of the joint, but also on the surface preparations further described in upcoming Sections 2.2.5 and 2.2.4.

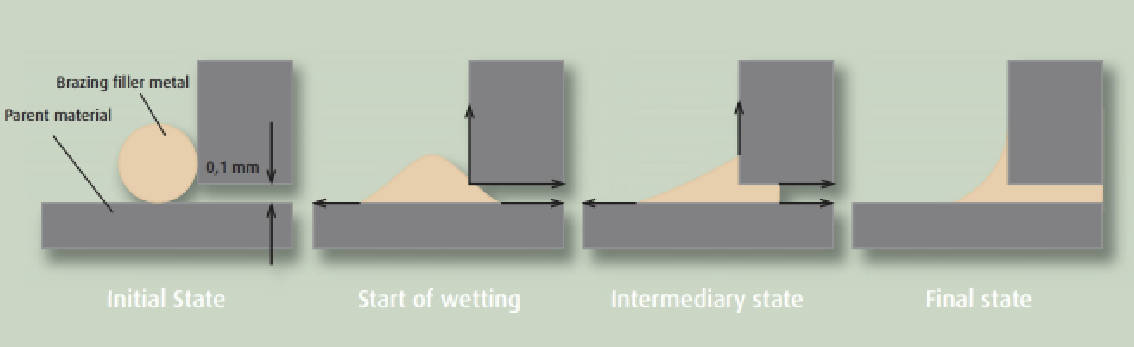

Figure 2.7: Illustration of the flow of the filler material in the gap. From the source *Principles of brazing and Soldering: Joining Technology* (Schnee and Materials, 2019), (s.12), by Schnee and SAXONIA Technical Materials, 2019. *Used with written permission.*

Another important factor for the flow of the filler material is viscosity. Filler materials with a narrow range between liquidus and solidus temperature have a lower viscosity than filler material with a wide temperature range. When it comes to the flow of the melted filler material, lower viscosity is better for the performance of the flow, described previously. The aim of the brazing process related to the flow of the filler material are (Jacobson and Humpston, 2005):

- To select a suitable filler material for the application of the joint and related to the base materials of the joint.
- To use a low working temperature as possible but still produce a flow of the filler material in the joint to save energy and time for the process.
- To keep the time at the working temperature as short as possible to save energy and time for the process.
- To cool down the joint, and to get the filler material below the melting temperature as fast as possible when desirable filler flow has been fulfilled into the joint, to prevent further flow.

2.2.4 Surface preparations

Clean surfaces are important to achieve sound joints. Insufficiently cleaned surfaces will result in uneven capillary forces and will affect the wetting and flow of the filler material. The main impurities on the surface of the base material in metal for brazing processes are AWS (2007):

- Grease, oil, and dirt.
- Oxides.

- Other solid or liquid impurities.

First must grease, oil, and dirt be removed before the oxides are removed. When the surface is clean and impurities are removed, uniform capillary action and wetting can be performed of the filler material flow during the brazing process. (Jacobson and Humpston, 2005).

Different types of cleaning processes of the metal surfaces can be done to remove grease, oil, and dirt (AWS, 2007):

- Chemical cleaning with different types of solvents, which dissolves oil and grease. The solvent can be petroleum-based, but also solvents like alcohol and acetone can be used.

Different types of cleaning processes of the metal surfaces can be done to remove oxides (AWS, 2007):

- Chemical cleaning like electrolytic cleaning to remove oxides from the surface.
- Chemical cleaning like acid cleaning to remove oxides, dirt, and grease.
- Mechanical cleaning like blasting to remove oxides.
- Mechanical cleaning with emery cloth to remove oxides. This is a cloth with very small abrasive grains attached to the surface of the cloth that carefully removes oxides and other irregularities of the surface on the metal. This can be done manually.

The cleaning process can however affect the roughness of the metal surfaces. This is usually not a disadvantage for the later brazing process, since a liquefied and molten filler material that wets a smooth surface, will in most cases wet a rougher surface even better. This is because a rougher surface will contribute to a more turbulent flow of the filler material in the molten state. When it comes to smoother surfaces, the flow will be more laminar. The turbulent flow will prolong the time and increase the ability for the metallurgical bonds to be stronger and denser (Jacobson and Humpston, 2005).

All metal surfaces inside an atmosphere that consists of air, have some oxide film even after cleaning of the surfaces. However, this will not affect the flow of the filler material. Worth mentioning is that it is important to perform the brazing process of the cleaned parts as soon as possible, due to more oxides building up at metal surfaces after time. When metals are heated in air, oxides will build up on the surface, which can be seen in Figure 2.8 when steel is heated in the air under time (Jacobson and Humpston, 2005). These oxides will act as a non-metallic barrier and prevent uniform capillary action and reduce the wetting action of the filler material (Schwartz, 2005).

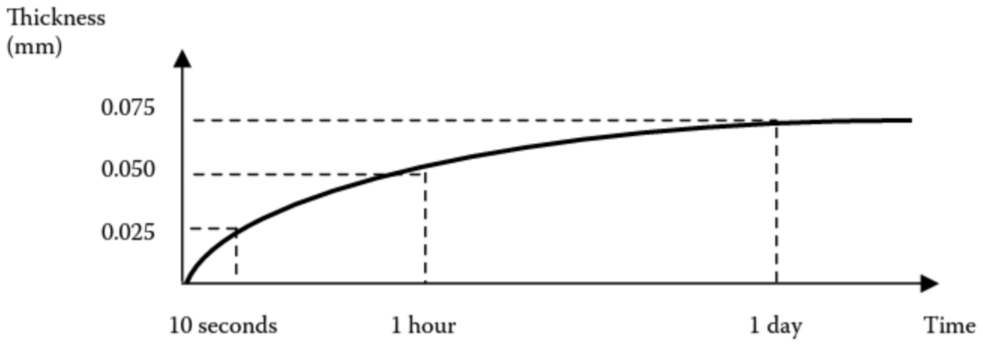

Figure 2.8: Rate of thickness increase of oxide on the surface of steel during heating in air . From the book *Industrial Brazing Practice* (Roberts, 2013), (s.87), by Philip Roberts, 2013. *Used with written permission.*

The brazing process that is performed in the air often requires some type of flux. The flux is used to clean and prevent oxides to form on the surface of the base materials by working as a separate agent. As previously described, wetting is essential for the sound joints during the brazing process and oxides are the main barrier to sufficient wetting. As Figure 2.8 describes, the oxide increases with temperature and therefore flux is used during the heating process. Fluxes used for brazing usually consists of metallic salts in different forms, such as paste or powder, that are solid at room temperature. To activate the flux as a separate agent, the material must be heated to the specific melting temperature. The lower the melting temperature, the more time it takes for the flux to remove the oxides before the filler material is melted. However, it is important that this effect decreases over time, see Figure 2.9. Additionally, fluxes with lower melting temperatures are unstable at higher working temperatures. It is therefore important to choose a flux that is adapted to the working temperature for the specific brazing application. The chemical composition of the flux must also be adapted (Roberts, 2013).

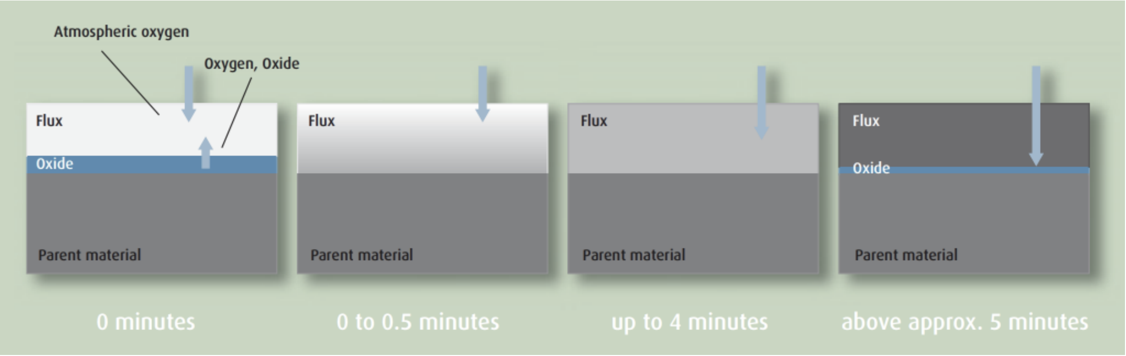

Figure 2.9: Illustration of the effect of the flux on oxides on the base metal (parent material). From the source *Principles of brazing and Soldering: Joining Technology* (Schnee and Materials, 2019), (s.12), by Schnee and SAXONIA Technical Materials, 2019. *Used with written permission.*

Different types of fluxes that usually is available on the market is described in Table 2.2 (Roberts, 2013):

Table 2.2: Different ingredients of mineral fluxes and it's properties.

Type:	**Typically base materials:**	**Typically filler material:**	**Activation temperature range °C:**
Caesium fluoroaluminate	Aluminium	Aluminium-Zinc	350 - 500
Chloride	Aluminium	-	500 - 660
Fluoroaluminate	Aluminium	-	570 - 660
Chloride-fluoride	Aluminium-Bronz	-	500 - 750
Fluoride	Almost all materials	Silver	550 - 800
Fluoride-borate	-	-	600 - 850
Fluo-borate	Steel-Tungsten	-	600 - 1000
Borate	Mild steel	Brass	750 - 1000

Brazing can also be performed in reducing atmosphere where either the whole brazing assembly is executed in a protection atmosphere (like in vacuum in a furnace) or a certain part can be protected by a shielding gas, like hydrogen, during the heating cycle (Schwartz, 2005). The gas used for this master's thesis project are stated in Table 3.3 in Chapter 3 as well as the properties of the flux used.

2.2.5 Design of the joint and gap

The design and dimensions of the including parts in the brazing assembly are of great importance for the strength and quality. Often the parts are made of different materials and manufactured in different ways which can affect the brazing result. The materials can in other words have different physical, mechanical, and chemical properties. Therefore, when the materials are exposed during the heating process, their properties can change and new properties can be created in the metallurgical bonds formed during the brazing process. Different properties like thermal conductivity, electrical conductivity, and thermal expansion affect the brazing process, as previously described with stainless steel and copper in Section 2.2.1. These properties will also affect the gap for the joint. The gap will not be the same before, under, and after the brazing process and this is something that has to be considered during the design. Gap for joints is defined at room temperature (Jacobson and Humpston, 2005). Some of the recommended gaps for different filler materials can be seen in Table 2.3 (Björklund et al., 2015) (Jacobson and Humpston, 2005).

Table 2.3: Different recommended gaps for different filler materials at room temperature (RT).

Type of filler:	Recommended gap at RT [mm]:
Silver (pre-placed)	0.050 - 0.200
Silver (manually added)	0.050 - 0.500
Aluminium	0.150 - 0.500
Copper	0.000 - 0.050
Phosphorus-Copper	0.030 - 0.130
Zinc-Copper	0.050 - 0.130
Gold	0.030 - 0.130
Phosphorus-Nickel	0.000 - 0.030
Chrome-Nickel	0.030 - 0.610
Palladium	0.030 - 0.100

The gap is the most influencing factor when it comes to the result of the brazed joints since it will affect the properties of the brazed joint, such as (Jacobson and Humpston, 2005):

- The possibility for voids to be created inside the joint when the filler material has solidified.
- The possibility for inter-metallic phases to be created inside the joint when the filler material has solidified.
- The strength of the joint.
- The capillary action and force which will distribute the filler material in the joint.

In most cases, small gaps are preferable due to a large capillary force and distribution of the filler material. Further, with an increase in distribution of the filler material in the joint, the likelihood of voids, inter-metallic phases, and shrinkage will decrease during the solidification of the filler material. Joint designs with small gaps create thin filler material films and in most cases, this will give sound joints. What is important to consider in the design of a joint and the width of the gap is that it depends on the following (Jacobson and Humpston, 2005):

- The filler and base material used.
- The flux used and the brazing atmosphere.
- Surface finish of the base material.
- How the filler material is placed (pre-placed or manually placed during the brazing).
- The heat source for the brazing (manual brazing or automatic like induction brazing).

Illustration of recommended gaps dependent on the brazing method and heat source can be seen in Figure 2.10.

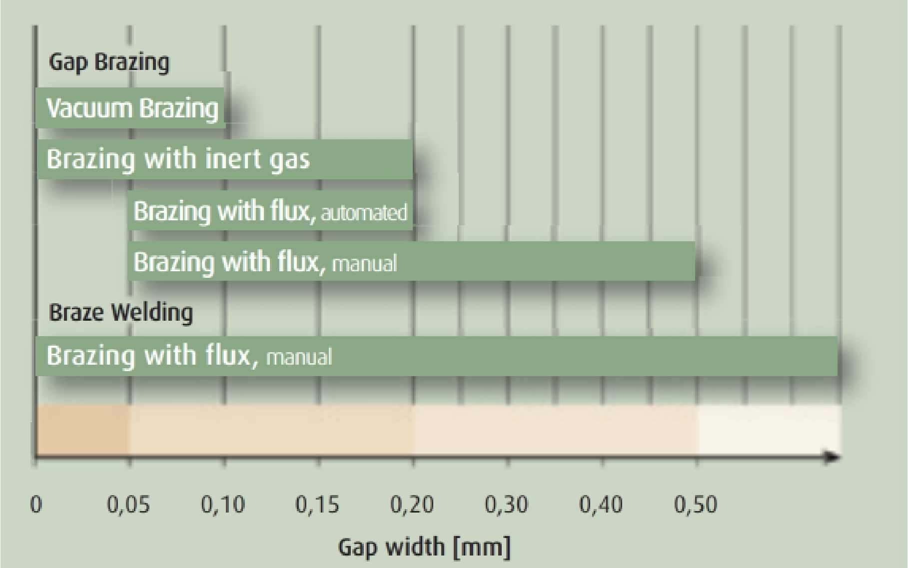

Figure 2.10: Different recommended gaps depending on the brazing method and heat source. From the source *Principles of brazing and Soldering: Joining Technology* (Schnee and Materials, 2019), (s.14), by Schnee and SAXONIA Technical Materials, 2019.
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During brazing of cylindrical components, it is also important to consider having the material with a higher thermal expansion coefficient on the outside of the joint to get the right stress requirements. Connected to this, thermal expansions from the different materials in the assembly will affect the gap during the brazing process. Either will the gap expand or close during the heat cycle and in the worst case prevent the flow of the filler material into the joint. Important is also the type of joint, related to how the filler material will be placed. If the filler material will be pre-placed with pre-forms, the joint has to consider the influence of gravity on the molten filler material. It should also be easy for operators to place the pre-forms. Another consideration when cylindrical components are brazed is the importance of concentricity of the including parts of the assembly related to each other. The concentricity will affect the gap and cause an uneven joint gap, which will create an uneven flow and probably an insufficiently filled joint that can create voids and other inclusions. The solution for this can be fixtures or to design the parts with chamfers to center the parts right with help of the assembly construction (Jacobson and Humpston, 2005).

When it comes to the joint length of the brazed joint, it is commonly recommended to have the length of the joint three times the thickness of the thinnest part of the brazing assembly. For example, if an assembly consists of two circular pipes that will be joined: Pipe 1 has an inner diameter of 20 mm and a thickness of 3 mm, and Pipe 2 has an outer diameter of 19,5 mm and a thickness of 2 mm, the length of the joints is recommended to be 6 mm (Björklund et al., 2015).

2.2.6 Temperature and time

The temperate of the heating cycle of the brazing process has an important effect on the wetting ability of the filler material in the molten state. The temperature and time also affect the diffusion between the base and filler material. It is important to have the right heat cycle during the brazing process. The temperature must melt the filler material, but at the same time not melt the base material. In combination with the temperature, the time will affect the flow of the filler. Too much heat (temperature) and time will draw the filler material too deep into the joint and maybe heat affect the base material too much. The combination with to little heat (temperature) and time can cause all alloying elements which are included in the filler material, do to not fully melt and the risk of a not filled and not wetted joint as a result. When it comes to full-scale production of brazed joints, the aim is to keep temperature and time as low and short as possible to (Jacobson and Humpston, 2005):

- Keep the energy consumption as low as possible and the process as effective as possible.
- Keep the heat effect on the base materials as low as possible to reduce the risk for grain growth with more that follows at high heat image.
- Keep the heat effect on tools and other equipment related to the brazing process.

An ideal heat cycle can be seen in Figure 2.11 below and different stages is further described below (Roberts, 2013).

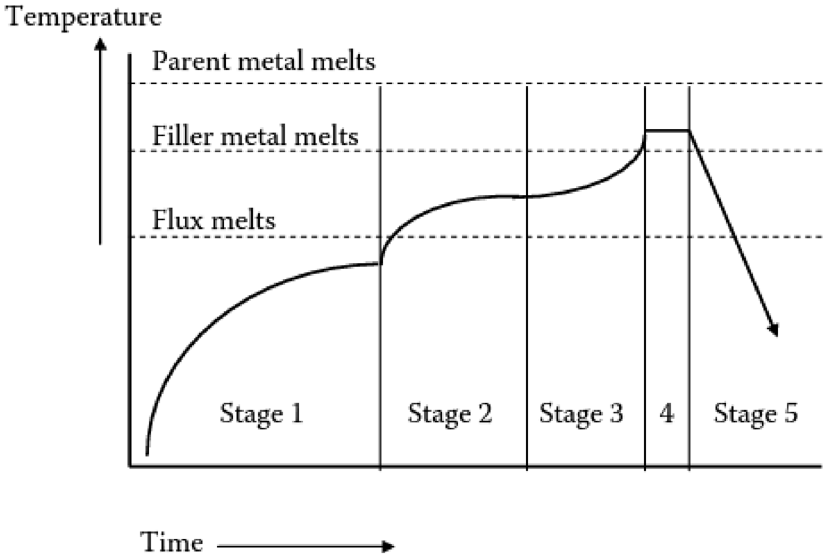

Figure 2.11: An ideal heating cycle of the brazing process illustrated. From the book *Industrial Brazing Practice* (Roberts, 2013), (s.22), by Philip Roberts, 2013. *Used with written permission.*

Stage 1: During stage 1 the aim is to heat the cold base materials (parent materials) to higher temperatures, observe that the flux does not need to melt during this stage. Stage 1 can be heated with a fair amount of energy and have a fast heating curve. Depending on the mass of the base materials and the including parts of the brazing assembly, the heating process may be paused to allow heat to flow to different parts, but also to the core of the parts.

Stage 2: During stage 2 the aim is to get to the temperature above the melting point of the flux. This will activate the flux, and it is important that the flux obtains time to wet the surfaces sufficiently to enable good surface conditions for the joints.

Stage 3: After the flux has wet the surfaces during stage 2, the aim of stage 3 is to pre-heat the assembly of the filler material in the next stage.

Stage 4: During stage 4 the aim is to hold the temperature above the temperature that allows the filler material to flow and spread into the gap of the joint. This is a critical time due to this is during this stage the "joint" is created and it is here voids and inclusions can be created in the joint under unsatisfactory conditions. At the end of this stage no more heat energy is added to the joints.

Stage 5: During stage 5 the aim is to cool of the joints.

2.2.7 Heat source

The most common heat sources for brazing are (Jacobson and Humpston, 2005):

- Torch brazing.
- Induction brazing.
- Furnace brazing.
- Resistance brazing.
- Dip brazing.

Induction brazing is further described in Section 2.3 below and will be the heat source this master's thesis will focus on. Worth mentioning is that, compared to torch brazing which is one of the most common heating methods, induction brazing has a higher capital cost and less versatility than torch brazing. At the same time, it requires fewer skills of the operator and can produce higher quality joints due to equal and known process parameters each time (Jacobson and Humpston, 2005).

2.3 Induction brazing

Induction brazing is an induction heating process that joins a workpiece (a brazing assembly), by heat created by the resistance that occurs from the flow eddy currents in the brazing assembly. The resistance against the current inside the workpiece will elevate the temperature. This temperature raise will eventually melt the filler material and a joint is created after solidification (Rudnev et al., 2017).

Induction brazing is performed by an induction machine that consists of a frequency converter (generator) that converts power from the electricity network to single-phase power. This power is then sent as altering voltage to the main part of the induction machine, the induction coils, in a specific frequency. The coils is water-cooled copper tubes and can be designed in different sizes, shapes, and number of turns. The coils are often designed for the specific brazing workpiece, due to that the design of the coil has to be adjusted to the application to achieve sound joints, this is an important factor. The purpose of the induction coils is to heat the joint of the workpiece in an even way and distribute the temperature in a uniform way (Jacobson and Humpston, 2005) (Rudnev et al., 2017).

The alternating voltage that is applied to the coil from the generator will then create an alternating current (AC) inside the coil. The AC with its frequency will then produce a time-variable magnetic field around the coil (which the workpiece is placed inside). Important to note is that it is not only the workpiece that is affected by the magnetic field but also objects in the surroundings within a certain distance from the coils. At a certain distance from the coil and its electromagnetic field, will Eddy currents be induced in the workpiece by the electromagnetic field. This current flows through the workpiece (mainly at the surface of the workpiece) and the workpiece will act as a conductor. This flow of the currents will induce thermal heat through the natural resistance to flow by the material of the workpiece. This will raise the temperature of the workpiece at the heat-affected zones. This will eventually heat the filler material to brazing working temperatures and melt the filler material (Rudnev et al., 2017).

Some of the factors that affect the heating of the workpiece are (Roberts, 2013):

- The thermal conductivity and thermal capacity of the workpiece.
- The distance the workpiece has to the coils of the induction machine.
- The frequency of the AC current in the coil.
- The rate of power delivered from the generator to the coils.

Some of the electromagnetic phenomena that affect the induction brazing process are described in Section 2.3.1.

2.3.1 Induction heat electromagnetic phenomena

The current distribution inside the coil and inside the workpiece is not uniform, which also affects the heating of the induction process. This is due to some different heat electromagnetic phenomena. Some of them are described below and they are:

1. Skin effect.
2. Proximity effect.
3. Ring effect.
4. End effect.

The Eddy currents created by the electromagnetic field will be concentrated to the surfaces of the workpiece, which is called skin effect. This effect occurs always in different degrees when an AC flows through a conductor. The degree of skin effect is dependent on the frequency of the AC in the electromagnetic field. Higher frequency on the AC will lead to that the Eddy currents will be closer to the core of the workpiece, compared to lower frequency AC where the currents will be more concentrated to the surface of the workpiece. This in turn will concentrate the heating procedure of the workpiece to the surface (depending on the frequency and the depth of the Eddy currents) of the brazed workpieces (Rudnev et al., 2017), see Figure 2.12.

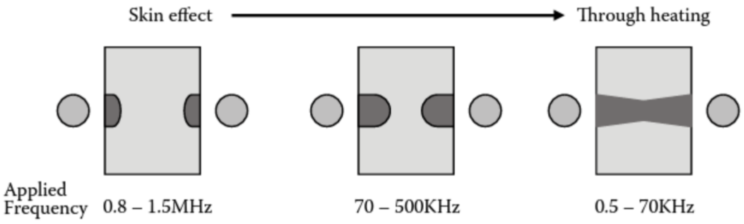

Figure 2.12: Illustration of the skin effect related to the frequency of the AC. From the book *Industrial Brazing Practice* (Roberts, 2013), (s.165), by Philip Roberts, 2013.
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For example, a workpiece that involves several parts or other objects near the coils, will be affected by the electromagnetic field from the coils. The different parts will acts as conductors and create their own magnetic field with Eddy currents. These different magnetic fields can encounter with each other and can create an effect called the proximity effect. This effect can strengthen or weaken and in some cases disrupt the magnetic field in the workpiece that is supposed to be brazed. That can in turn change the skin effect and the currents in the workpiece and affect the heating procedure. Another thing that falls into the category of proximity effect is the symmetrical positioning of the workpiece inside the induction coil. It is important that the workpiece is centered in the coil to avoid the concentration of currents on one side of the workpiece and with the consequence of uneven heating procedure (Rudnev et al., 2017), see Figure 2.13.

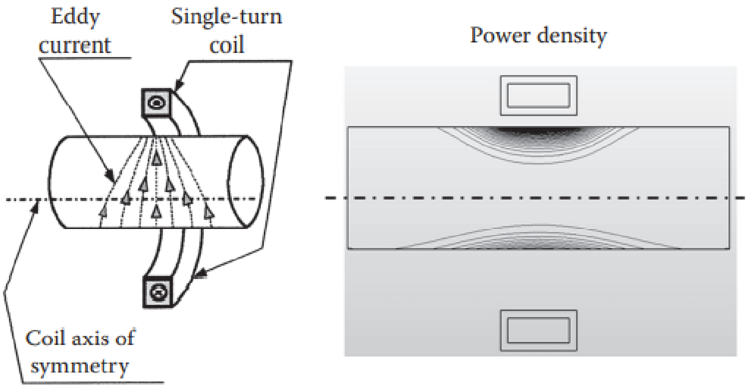

Figure 2.13: Illustration of the proximity effect from non-symmetrical positioning of the workpiece inside the induction coil. From the book *Handbook of Induction Heating* (Rudnev et al., 2017), (s.68), by Rudnev et al, 2017.
Used with written permission.

When a conductor inside the induction coil is shaped like a ring, an effect called ring effect occur. This means that the concentration of the current will be concentrated on the inside of the ring and will affect the heating procedure of the brazing process (Rudnev et al., 2017).

At the end of a coil, will the electromagnetic field drops drastically, called end effect. If the coil design is not properly adjusted to the assembly of the brazing process, there is a risk that some parts of the workpiece will be less affected by the electromagnetic field. This in turn will decrease the induced heat in the specific part of the workpiece and uneven heat distribution will occur (Rudnev et al., 2017).

2.3.2 Advantages and disadvantages of induction brazing

Some of the advantages of using induction brazing compared to other methods like flame brazing are (EFD, 2022)(Rudnev et al., 2017)(Roberts, 2013):

- The process offers selective heating of the brazing assembly, which means the heat-affected zones can be limited to the joint area of the workpiece.
- More energy per square millimeter can be induced compared with flame brazing, which in turn will lead to a decreased time of heat impact to the material of the workpiece. This will also decrease the throughput time of the brazed object.
- Due to consistent process parameters can consistent brazing results be expected by a stable process.
- A working induction brazing process requires no high skilled operators.
- Offers a highly automated process and products can be produced in high volume.
- The process can be highly controllable and the risk for overheating can be eliminated.
- The process is contact-less between the heat source (the induction coil) and the workpiece (brazing assembly) which offers cleaner surfaces after the process compared to flame brazing.

However their are some disadvantages (Rudnev et al., 2017)(Roberts, 2013) (Jacobson and Humpston, 2005):

- Expensive investment cost and equipment for induction brazing compared with flame brazing.
- The design of the coil limits the complexity for the workpiece compared with flame brazing.
- The induced heat is related to the distance from the coil, which will create a risk of a non-uniform heating process of the brazing assembly.
- The induction process requires accurate fit of the parts of the assembly, with recommended gaps between 0.050 - 0.130 mm to achieve sound joints, but some applications can get acceptable joints with gaps up to a maximum of 0.200 mm.

2.3.3 Estimation of required power supply for the induction heat process

Simple equations can be used to estimate the required power to raise the average temperature in a workpiece with a certain mass and heat capacity during a particular time frame. An example can be seen in Equation 2.1 (Rudnev et al., 2017).

$$P = \frac{m \cdot c \cdot (T_{initial} - T_{final})}{t} \tag{2.1}$$

Where P is the estimated required power for the induction brazing process that need to be absorbed by a workpiece with a mass, m, and specific heat, c, to raise the average temperature from $T_{initial}$ to T_{final} during a certain time, t. By this simple equation, estimations can be made to formulate settings and parameters from the induction generator and the coils included in the induction process to correspond to the recommended heat curve for a specific joint and its materials.

2.3.4 Influential parameters of induction brazing

In addition to the parameters related to ordinary brazing described in Section 2.2, there are some other influential parameters related to induction brazing (Ketchan, 2021) (Rudnev et al., 2017):

1. As mentioned in Section 2.3.1, the coil design and the positioning of the workpiece related to the induction coils are important parameters to be able to achieve sound joints.
2. Accurate and stable process of the induction machine is important. This means a machine that can supply stable power to the coils with the right amount of voltage and frequency. A non-stable process related to the induction machine, will in turn affect the induction brazing process of the joining process. To achieve maximum effectiveness of the coil, is it also important that the coil is provided by proper water cooling inside the coil itself to avoid overheating of the coils.
3. The materials of the base and filler materials need to be consistent. The heat distribution is dependent on the material composition, but also that the dimensions and shapes are consistent to achieve required joint gaps.
4. Due to that the induction brazing process is usually automated to some degree, fixture and centering of the part of the assembly is an important consideration in induction brazing. This is due to ensure repeated positioning accuracy of the part, but also to ensure that the gap of the joint is uniform around the joint during the heat cycle. This is essential to achieve sound brazed joints and to achieve a reliable production process.

2.4 Inspection of brazed joints

Inspection of the brazed joints is an important step in the manufacturing when a product is joined through brazing. This is due to discontinuities that can occur in the joints and some of the most common defects are described in Section 2.4.1. The type of inspection and requirements on a brazed joint are dependent on the service requirements for the end product of the assembly. Often are specifications and standards set for the inspection of the brazed joints that has detailed documentation of acceptable defects of the brazed joints. It is important that the operator that performs the inspections has knowledge about metallurgical bonds for brazing, but it is also important that the operator has an understanding of the function of the end product for the brazed assembly. Some of the different methods for inspection of brazed joints is described in Section 2.4.2 and 2.4.3 (AWS, 2007).

2.4.1 Potential defects in brazed joints

Some of the defects that can occur in brazed joints are:

- Voids.
- Entrapped flux.
- Cracks.
- Erosion of the base materials.
- Inadequate conditions of the surface of the joint.
- Discontinuous joint.

Voids in the brazed joint can reduce the strength of the joint and depending on the amount of the voids can it lead to leakage of fluid or gas for the end product. The voids arise by an incomplete flow of the filler material in the joint gap. Some of the potential causes for the formation of voids are (AWS, 2007):

- Inadequate filler material.
- Entrapped gas.
- Inappropriate joint gap.
- Movement of parts of the assembly when filler material is in the molten state. Can also be different thermal expansions of the including material in the assembly.
- Improper surface cleaning of the base materials.

Flux is used to reduce oxide formation during the brazing process, described in Section 2.2.4. After activation of the flux, the filler material melts and the flow of the filler material pushes the flux out of the joint. However, when the flux is used, it can get entrapped and prevent the filler material to flow in some areas of the joint. The main cause for entrapped flux is due to the design of the joint does not allow the flux to flow out of the joint (AWS, 2007).

Cracks in the joints or in the base materials act as stress raisers and reduce the strength of the joint. Erosion can occur in the base material during the alloying process with the filler material and can dissolve the base materials and affect the flow of the filler material. This can cause a reduction of the cross-section area of the brazed joint and reduce the strength of the joint. With inadequate surface conditions mean not fulfilled aesthetics considerations of the joints. It can be too rough surfaces or that filler material has flowed over the joint onto the surface outside the joint area, due to excessively used filler material. Discontinuity of the joint means that the surface of the joint is not uniform and this is often discovered during visual inspection of the joint (AWS, 2007).

2.4.2 Visual inspections

The most used inspection of brazed joints is the visual inspection. It is an effective method to detect imperfections at the surface of the joints, such as discontinuous joints or indications of voids. When a visual inspection is used as the primary inspection method of brazed joints, it is important at the beginning of a setup of a new brazing process, to ensure the process parameters achieve the requirements of the joints. To be able to ensure the process parameters for the brazing operation are sufficient, also other non-destructive methods can be used, such as radiographic inspection. This is due to visual inspection being only limited to externally quality inspection of joints. Even if a joint has a continuous filling of the filler material, can still imperfections like lack of filling and voids occur internal in the joint and reduce the quality of the end product of the brazing assembly (AWS, 2007).

2.4.3 Radiographic inspections

Radiographic inspection, X-ray inspection, is one of the most used methods of non-destructive inspection of brazed joints. Radiographic inspection means that X-rays are directed from an X-ray-source trough a joint. The X-rays are then captured by film behind the joint. During this process are some of the X-rays absorbed by the material in the joint, which will create an image in the film. During X-ray inspection is it important to consider that the base materials and the filler material could have different absorption characteristics of the X-rays, which can affect the outcome of the inspection. Important to note is that X-ray inspection has some limitations. In most cases, the method does not accomplish to detect impurities in the joint that is 2 % or less than the cross-section of the joint. Metallurgical bonds can also not be seen in the joint (AWS, 2007).

3

Method

This chapter describes the methods for the included literature study and the method used to investigate the induction brazing process at the company. The chapter ends with a description of the experimental study that investigated different process parameters for the induction brazing of the circular pipes.

3.1 Literature study

To understand the brazing process and to get an understanding of the fundamentals of brazing, was a literature study performed. The literature study started with a study about the overview of brazing and its fundamentals. The basic concepts of brazing were covered and how the metallurgical bonds were formed during the brazing process. The base- and filler materials properties were covered and how the heat cycle can affect the result of the process. During the later part of the literature study, was induction brazing covered and what types of defects that can occur during the formations of the brazed joints and how these can be identified.

When the foundation of the basics for brazing was covered, the purpose was to identify potential influential parameters for the existing brazing process at the company. The literature study was an ongoing work along with the master's thesis project and relevant information covered in the study was later used in the parallel ongoing experimental study.

The literature study was carried out by searching for and reading relevant books, e-books and articles about the topic of brazing and induction brazing. Most of the online sources were found through Chalmers University of Technology online library service and in databases like:

- ProQuest platform.
- ScienceDirect.
- Knovel.
- eBook Index.

Key words that was used during the literature study was among others; *Brazing*, *Induction brazing*, *Filler materials*, *Base materials*, *Heat cycle*, *Parameters affecting brazing*, *Microstructure of joints*.

Relevant information was also covered through reliable websites. Valuable information was also collected through contact with suppliers of filler materials and induction brazing equipment, who had years of experience with their specific products.

3.2 Existing brazing process study

To get a deeper understanding of the cause of the unfulfilled quality requirements of the brazing process, a study was carried out regarding the existing brazing station at the company. Materials and equipment characteristics were investigated. Related to the equipment, the efficiency of the coils for the induction process was investigated through a heat examination test. Furthermore, was the dimensions and tolerances of the selected materials studied to examine the range of gaps related to the brazing process. At the end of the existing process, the amount of filler material was calculated related to the volume of the joint volume to ensure that the right amount of filler material was used.

3.2.1 Materials and equipment

The type of joining method used at the company to join the pipes was induction brazing, with a brazing temperature above $450°C$ during the process. The filler material is manually pre-placed on the pipes before the brazing process, see Figure 1.1, and had a shape of rings. Concerning the shape of the parts that are joined, it is a column brazing process where the surfaces of the base material (that will be joined to each other) is parallel to each other with a gap between them. Protection gas is used inside the pipes and flux is brushed on the joint before the induction process. The material of the pipe for the base material was copper. The material for the fitting pipe of the base material was stainless steel. The filler material used was silver-based, and the flux was a fluoride-borate salt-mixture paste. A filler material that was flux-integrated based on silver was also used during the experimental part of this master's thesis project. Important to note is when flux-integrated filler material was used, no flux was brushed on the connections before the brazing process. Two different connections, NR3 and NR4, were examined. Each connection consisted of a fitting pipe of stainless steel that was joined with a pipe of copper. The different connections had different dimensions, hence the different names for them. The interface with the dimensions for NR3 and NR4 can be seen in Figure 3.1, the maximum joint length for each connection was 15.6 mm.

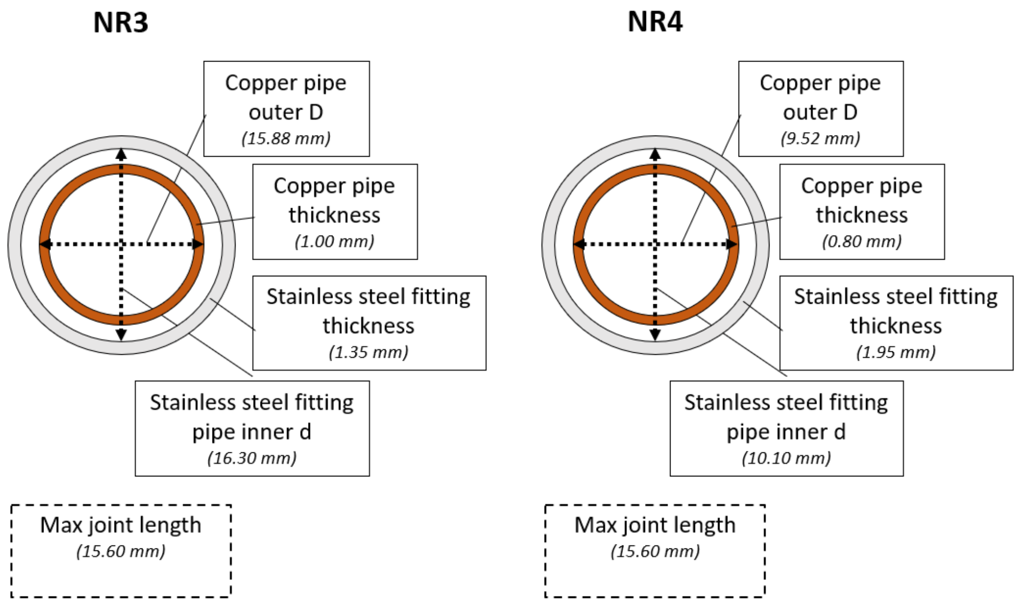

Figure 3.1: The interface for connections NR3 and NR4.

The base material was pre-determined in the design of the product. The filler material was examined through product sheets where the interval for the melting range was identified, which in turn was used to create the right heating cycle for the brazing process that was matching the melting range of the filler material. Through product sheets about the base materials, could heat conductivity, thermal expansion, and heat capacity, and melting temperature be identified and used to see how these properties would affect the brazing process during the heat cycle.

Different properties of copper and stainless steel used as base materials for this master's thesis project can be seen in Table 3.1 (Holme Dodsworth Metals Limited, 2022) (Metalcor, 2022).

Table 3.1: Base material properties of the used pipe of copper and fitting pipe of stainless steel.

Material:	**Copper**	**Stainless Steel**
Thermal conductivity [W/m°K] :	340	15
Specific heat capacity [J/Kg°C]:	385	500
Thermal expansion [10^{-6}°C]:	17	16
Density [Kg/m^3]:	8940	8000
Melting temperature [°C]:	1083	1400 - 1450

Material properties of the silver-based filler materials used can be seen in Table 3.2, both the solid silver-based filler material and the flux-integrated silver-based filler material.

Table 3.2: Properties of the used filler materials.

Properties:	**Solid:**	**Flux-integrated:**
Solidus temperature [$°C$]:	650	650
Liquidus temperature [$°C$]:	710	720
Working range [$°C$]:	650 - 710	650 - 720
Percent silver content [%]:	40.7	38
Percent copper content [%]:	29.3	28
Percent zinc content [%]:	28	32
Percent tin content [%]:	2	2
Percent flux content inside filler material [%]:	0	≈ 15

Properties of the used flux and protection gas can be seen in Table 3.3.

Table 3.3: Flux and protection gas used for the master's thesis project. The flux is a salt mix of potassium fluoroborates and contains no boric acid or borax. The process is performed in air, but nitrogen is used inside the pipes.

<table>
<tr><th colspan="4">Flux used:</th></tr>
<tr><td>Type:</td><td>Typically base materials:</td><td>Typically filler material:</td><td>Activation temperature range $°C$:</td></tr>
<tr><td>Fluoro-borate</td><td>Copper, Copper alloys, Steel, Stainless steel</td><td>Silver-based</td><td>600 - 800</td></tr>
<tr><th colspan="4">Protection gas used:</th></tr>
<tr><td>Type:</td><td>Application space:</td><td>Purpose:</td><td></td></tr>
<tr><td>Nitrogen</td><td>Inside pipe</td><td>Protect inside of pipe from oxidation</td><td></td></tr>
</table>

The induction brazing machine used at the company consisted of two coils, one for NR3 connection which was given the name H1, and one for NR4 connection with name H2, which could be run simultaneously or separately. The coils had the shape of a U and on each long side of each coil, an amplifier was attached to increase the the magnetic field of the coil. Specifications for the used induction brazing machine can be seen in Table 3.4. Different programs with including segments could be programmed on the induction machine to create different heat curves of the induction brazing process. Parameters for the programs that could be controlled relevant for this project were the percentage of current and the time for each segment. Important to mention was more energy and more power were required to heat connection NR4 with coil H2 compared to NR3 and H1.

Table 3.4: Specification for the used induction brazing machine.

Characteristics:	**Value**
Number of coils [pcs.]:	2
Supply voltage range 3 phase [V]:	400 - 480
Supply frequency [Hz]:	50/60
Supply nominal voltage [V]:	400
Supply nominal line current [A]:	22
Supply nominal apparent power [kVA]:	15
Output nominal power [kW]:	2x6
Output power regulation [%]:	2 - 100
Output DC power [kW]:	2x10
Output maximum current [A]:	150
Output maximum frequency [kHz]:	100

3.2.2 Investigation of the design of the coil

Due to each coil having the shape of a U (even with the amplifiers) there were a risk for "cold" spots where the coil is not closed around the pipes. This can affect the melting process of the filler material. Therefore, an investigation of the efficiency of the design for the coils was done by heating the connection with the including pipes, without any filler material applied. This was done to be able to see the oxide formation on the copper pipe which shows clear oxide formation during heating. In theory, possible "cold spots" in the design of the coil shown in the oxide formation with more or less formation of oxides around the pipes. By knowing how the pipe had been placed during the heat cycle related to the coil, the copper pipes could then be examined after the heat cycle. A video camera was also used to record each connection (NR3 and NR4) during the heat cycle to be able to examine the formations of oxides overtime during the heat cycle. Five pipes and five runs of the machine program per connection were performed. The used program on the induction machine to investigate the effectiveness of each coil (H1 and H2), can be illustrated in Figure 3.2, called Program 0.

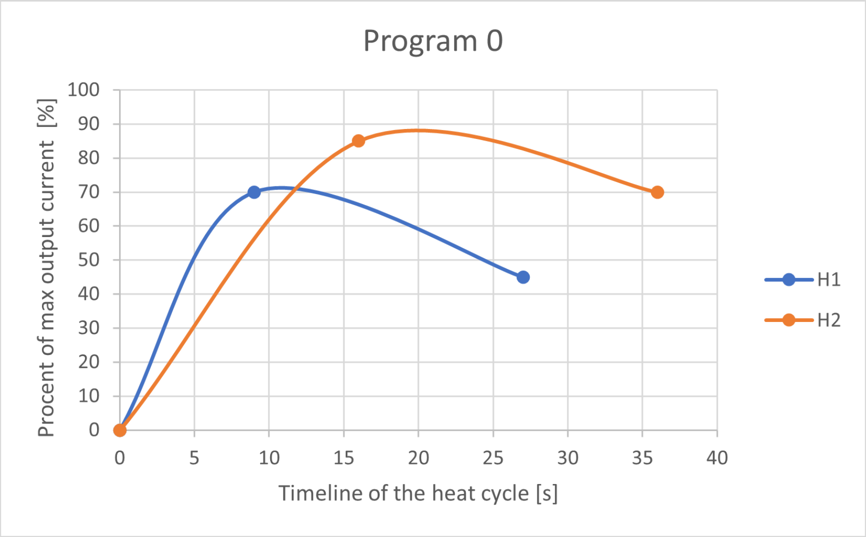

Figure 3.2: Illustration of induction machine Program 0 for coil H1 and H2, respectively.

3.2.3 Tolerances and gaps for the joints

Gaps for the joints that are created by the copper pipe and the stainless steel fitting pipe were calculated by examining technical drawings for each connection. Maximum and minimum gaps were calculated through Equation 3.1, where $d_{stainless}$ are the inner diameter for the stainless steel fitting pipe and D_{copper} was the outer diameter for the copper pipe. The maximum gap was calculated with the maximum inner diameter of the stainless steel fitting pipe in combination with the minimum outer diameter of the copper pipe. The minimum gap was calculated with a minimum inner diameter of the stainless steel fitting pipe in combination with the maximum outer diameter of the copper pipe. An illustration of the measurement of gaps can be seen in Figure 3.3. During the experimental part, was each joint gap was measured with a caliper before the brazing process. This was due to be able to follow up the gap for each connection/joint and the gap was calculated with the help of Equation 3.1.

$$Joint\ gap = \frac{d_{stainless} - D_{copper}}{2} \tag{3.1}$$

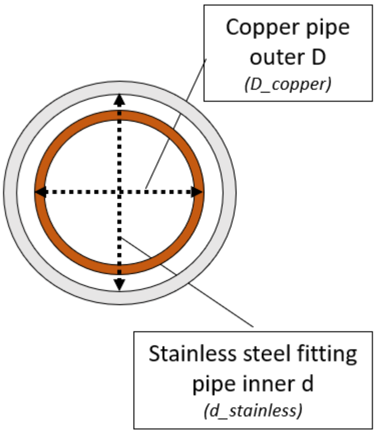

Figure 3.3: Illustration of measurement of gaps for the connections and joints.

3.2.4 Amount of filler material for the joints

The amount of filler material was calculated to be able to see that enough amount of material was used to fill the joint. The amount of filler material was calculated with the maximum gap for each connection together with the maximum joint length. The joints had two requirements for the degree of filling of the joint. Both requirements did not have to be fulfilled at the same time, it was enough for only one of the requirements to be fulfilled. The requirements for the joints were:

1. 70 % joint filling of 5 mm from the top of the joint.
2. 70 % joint filling of the total maximum joint length, 15.6 mm.

Requirement two was used when the amount of filler materials for the joints was calculated for the ordinary filler material that was pre-placed at the joint for the induction brazing. It was calculated with Equation 3.2, where $d_{stainless}$ is the inner diameter for the stainless steel fitting pipe, D_{copper} the outer diameter for the copper pipe and L_{joint} the maximum joint length.

$$Amount\ filler\ material = (\frac{L_{joint} \cdot \pi}{4} \cdot (d^2_{stainless} - D^2_{copper})) \cdot 70\% \tag{3.2}$$

The amount of the alternative filler material with integrated flux was calculated from the supplier. The different amount for the solid filler material and the flux-integrated filler material was compared with the manual brazing flame brazing process for the same product as this master's thesis had its focus on. The manual brazing process used rods that were placed manually during the process, instead of pre-placed preforms of filler material that was used during the induction brazing process. Average values of used filler material for the manual brazing was taken from previously collected data by the company.

3.2.5 Formulation of induction machine programs

The induction machine Program number 4, which can be seen in Figure 3.4, was the existing program at the beginning of the master's thesis project. Program 4 was set as a reference and was used to create alternative programs for the induction brazing process. Program 4 was used with the solid filler material described in Table 3.2.

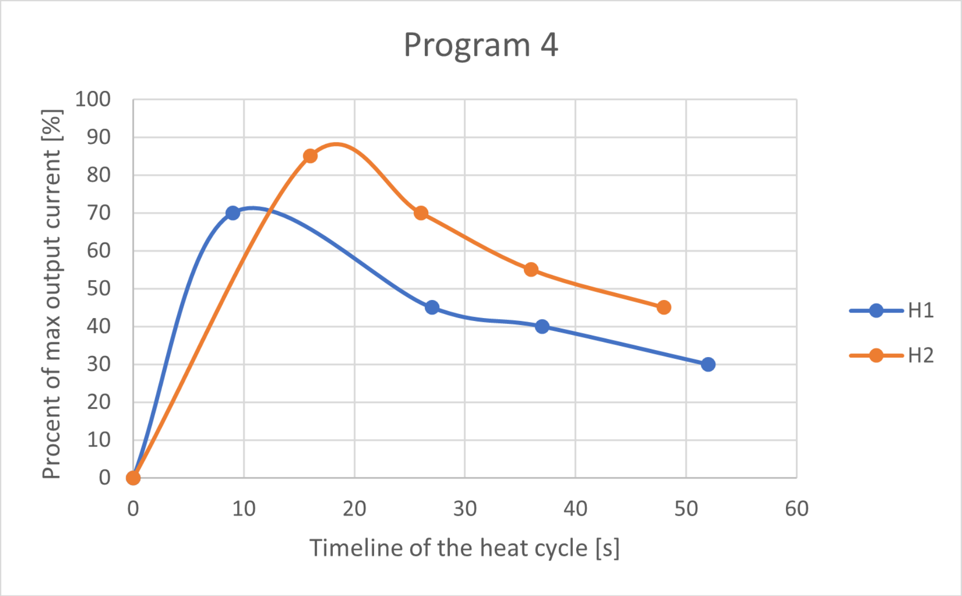

Figure 3.4: Illustration of induction machine Program 4 for coil H1 respectively H2.

Program 4 was used to create programs for the experimental part of the master's thesis project about the induction brazing process and station. To be able to create programs that was matching the melting range for filler material and to control the brazing process, an IR-thermometer was used. To be able to hold the IR-thermometer steady and in position during the whole heat cycle, a fixture was built. The fixture could be adjusted in height and adjusted in 360 degrees. The surface temperature was measured with the IR-thermometer on each connection (NR3 and NR4 connection) during the brazing process for each segment. Program 4 included four segments with different settings for current and time, giving out different values for power and frequency to the coils. Five measurements were collected per connection and coil to get reasonable values on the average temperature for each segment.

Through the display from the induction machine, the following parameters were read for the different segments for Program 4: time, current, and power. This was the output the machine produced to the coils for the induction process. These values could then be compared to the surface temperature of the joints with the IR-thermometer. These values could then be combined to formulate Equation 3.3 that was described in Section 2.3.3 that calculates the absorbed power in the material of the joint from the power from the induction coil from the induction machine, $P_{calculated}$. By this, the power from the machine for a specific segment could be compared with absorbed power in joints for the same specific segment of the program. T_{final} is the temperature measured with the IR-thermometer for the specific segment. $T_{initial}$ is the measured temperature before the specific segment, c_{joint} is the specific heat for the joint, and the value for this was chosen the specific heat of the stainless steel, 500 J/Kg°C, that can be seen in Table 3.1. The stainless steel value was chosen due to more heat is required to heat the steel compared to the copper, in other words, more power required to heat the stainless steel part of the joint. m_{joint} is the total mass of the joint, the mass of the fitting pipe of stainless steel in the combination with the mass of pipe of copper, for each connection (NR3 and NR4). The mass for each connection (NR3 and NR4) was calculated with help of technical drawings and is hidden due to secrecy. t is the time for the specific segment of the induction program.

$$P_{calculated} = \frac{m_{joint} \cdot c_{joint} \cdot (T_{initial} - T_{final})}{t} \tag{3.3}$$

By having the power and the current for the machine, $P_{machine}$ and $I_{machine}$, could the resistance for the coils, R_{coil}, be calculated for each segment and coil by Equation 3.4.

$$R_{coil} = \frac{P_{machine}}{I^2_{machine}} \tag{3.4}$$

By having the values of the calculated absorbed power, $P_{calculated}$, from Equation 3.3 and the power from the machine, $P_{machine}$, the efficiency for the induction machine, $E_{machine}$, could be calculated for each segment by Equation 3.5.

$$E_{machine} = \frac{P_{calculated}}{P_{machine}} \tag{3.5}$$

Program 4 included four segments, four values for R_{coil} and four values for $E_{machine}$ were created from the measurements. An average value for R_{coil} and $E_{machine}$ was created. Important to note is that it was different values for R_{coil} and $E_{machine}$ between the different connections and the related coil to the connections. By using the average values, new programs with new segments could be created with the help of Equation 3.6. Through this, the needed current, I_{needed}, could be calculated through determination on which temperatures, $T_{initial}$ and T_{final}, to be reached during each segment and at what time the temperature should be reached for each connection and coil. Further, induction machine programs with adjustment segments including settings for time and needed current could be created for the induction machine. These programs and including segments could in other words be adjusted to the melting range for the filler material and be able to create different heat curves for the induction brazing process.

$$I_{needed} = \sqrt{\frac{m_{joint} \cdot c_{joint} \cdot (T_{initial} - T_{final})}{t \cdot R_{coil} \cdot E_{machine}}} \tag{3.6}$$

An important note was when the programs for the flux-integrated filler material were made, a more gentle heating rate at the beginning of the program was used, compared to the solid filler material. This was due to information from the supplier of the flux-integrated filler. In order for the flux inside the ring to come out of the ring and have time to melt and act on the surface of the base materials, more time was needed in the beginning, before the filler material itself was melted.

3.3 Experimental study

The experimental study consisted of different types of tests with different parameters and settings used during the induction brazing process, all done using the induction brazing machine at the company. The different parameters that were examined were:

- The heat curves (time and current settings in the induction machine programs).
- Filler materials.
- Surface preparations
- How the flux was applied.
- Amount of flux applied.

In total was 90 products (each product consisted of one connection of NR3 and one connection of NR4) were tested in the experimental study. The experimental study, test plan, and its procedure are further described below in Section 3.3.2. Before each new induction machine program, was the program investigated through a temperature control with an IR-thermometer.

3.3.1 Investigation of induction machine programs

As mentioned previously, an IR-thermometer was used before each induction program was used in the test plan. The reason for this was to investigate how high the temperature was for each connection and related segment in the induction machine program. The investigation was carried out by running the different programs on the induction machine on the connections (NR3 and NR4) without any filler material used. The temperatures were recorded by the IR-thermometer which can be seen in Figure 3.5. Important to note is that the temperature measured was the surface temperature, and just as mentioned in Section 2.3, is that the core temperature may differ from the surface temperature. The emission factor used was 0.77 which is the average value for copper and stainless steel. Through this investigation the programs could be evaluated to see if the temperatures were too high, which would heat damage the parts, or too low, which would cause a risk that the filler material would not melt properly.

Figure 3.5: Illustration of surface temperature measurements with the help of the IR-thermometer of the connections (connection concealed in the figure).

3.3.2 Experimental studies of different parameters

After the temperature investigation, the program was elevated and a decision was made if it should be used or not. The final test plan used in this master's thesis, including 90 products, can be seen in Appendix A. Each product that consists of one NR3 and NR4 connection was given an Ex nr (Ex nr stands for "Exjobb number" in Swedish which means "Master's thesis number" in English). The products were tested in batches consisting of 10 products, and in total 9 batches were tested. The different parameters tested included different heat curves of temperatures and times in the different induction machine programs, how the surface of the connections was prepared, different filler materials, how the flux was applied, and the amount the flux was applied at the connection before the induction brazing process. For each induction brazing process for the 90 products, the flow of the protection gas was constant at a value of 8 l/min. The goal for each test of the product was to get visually approved joints for both connections and the working procedure for each batch is further described below. The result for each product is presented in Chapter 4. When the test of the joint from a product (Ex nr) achieved satisfactory visually approved results, the product was sent to X-ray examination internally at the company.

The ordinary amount of filler material used was two rings for the solid material and one ring for the flux-integrated material. This amount was compared with the results from the filler amount Equation 3.2 that is presented in Chapter 4. The surface preparations that were used to prepare the surfaces for the copper pipe and the stainless steel fitting for the connection NR3 and NR4 were divided into four categories:

- **None:** No surface preparation on the pipe and the fitting.
- **Mechanical nr 1:** Polish with nylon sanding sheet (can be seen in Figure 3.6) and dry cloth (can be seen in Figure 3.6) to remove waste.
- **Mechanical nr 2:** Polish with nylon sanding sheet and with emery cloth with

grain size P400 (can be seen in Figure 3.6) and dry cloth to remove waste. A nylon sheet was also used to polish the filler material.

- **Chemical:** T-röd (ethanol based liquid) and citric acid (20 %) and dry cloth to remove waste.

The purpose of mechanical surface preparations was to remove surface oxides on the parts. The purpose of the chemical surface preparations was to remove grease, dirt, and to some extent surface oxides. During the use of the chemical category, plastic gloves were used to protect the hands from acid and to avoid additional grease being applied to the surfaces.

Figure 3.6: Illustration of the objects used for the mechanical surface preparation of the connections.

The amount of flux used was either a generous amount or a little amount. To test if entrapped flux was a potential cause for voids and inclusions. Then the flux was brushed on the connection in two ways, as illustrated in the Figure 3.7 and described below:

Above rings: The flux was brushed above and on the rings that was pre-placed on the copper pipe before the induction brazing process.

Under rings: The flux was brushed under the rings that was pre-placed on the copper pipe before the induction brazing process. Little amount was also applied at the ring closest to the fitting direction .

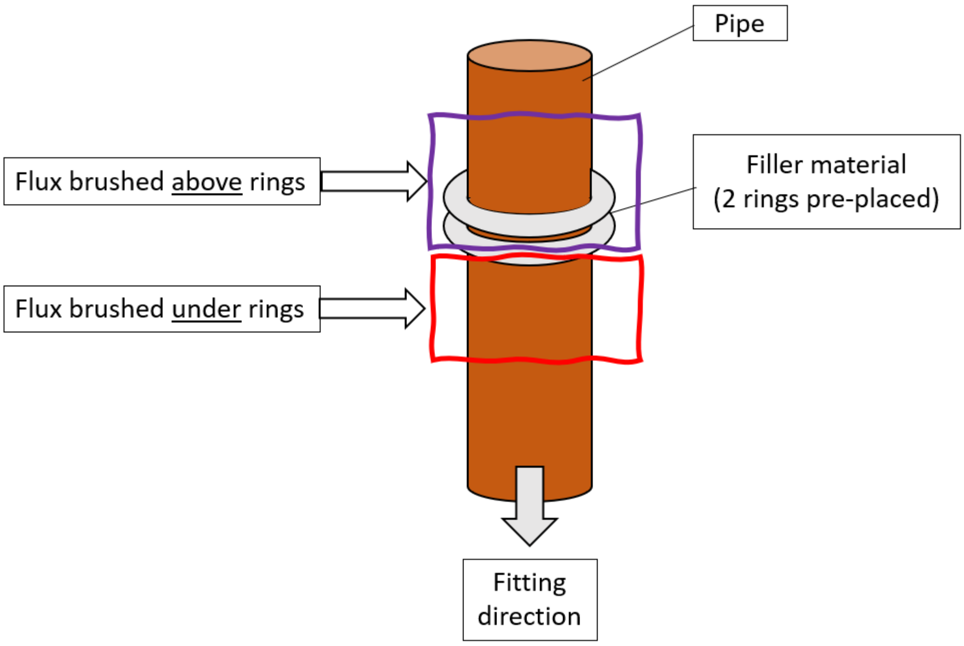

Figure 3.7: Illustration of the two different ways of which the flux was applied.

In the following paragraphs is a short description of the parameters used for each batch. Results of the induction brazing process for each batch and product (Ex nr) are presented in Chapter 4. Different programs and versions were used since either the filler material were different, to achieve visually approved joints, or to modify the heat curve. During the experimental studies, all connections for each product were measured and the gap for each joint was calculated with Equation 3.1. The complete test plan can be seen in Appendix A and complete settings for each induction machine program can be seen in Appendix B in figure-form. In Appendix C can the complete induction machine programs in table-form be found.

Batch 1 (Ex nr 1 - 10)

For Batch 1, the five first products (Ex nr 1-5) were used to test Program 1. Ex nr 1-3 had Mechanical nr 1 surface preparation, while no surface preparation was used for Ex nr 4-5. Further, for Ex nr 6-8, Program 1 were adjusted with Equation 3.6 and named Program 1_1. The reason was to decrease the temperature of the connections. Also, Mechanical nr 1 surface preparations were used. For Ex nr 9-10 Program 1_1 were in turn adjusted with Equation 3.6 and named Program 1_2 to even further decrease the temperature of the connections. However, no surface preparation was done. The purpose of using Mechanical nr 1 surface preparation on some of the products was to see if the filler material behaved differently in the molten state. On all products, in Batch 1 the flux was applied above the rings and with a generous amount. The solid filler material was used.

Batch 2 (Ex nr 11 - 20)

For Batch 2, Program 1_2 was used and for all products, Mechanical nr 2 surface preparations were performed (with the emery cloth that removes more oxides than only the nylon sanding sheet). The purpose was to see the difference in X-ray with surface oxides removed. On all products in Batch 2, the flux was applied above the rings and with a generous amount. The solid filler material was used.

Batch 3 (Ex nr 21 - 30)
For Batch 3, Program 1_2 was adjusted with Equation 3.6 and named Program 1_3 to get a slower temperatures solidification and to increase the temperature of the filler material during the brazing process. At the same time, it should be avoided that the filler material melts too far into the joint. The theory was that higher temperatures would increase the viscosity of the filler material and thus reduce the risk of bubbles and inclusion, mentioned in Section 2.2.2. At the same time, the amount of flux were reduced to decrease the risk of entrapped flux inside the joints also mentioned in Section 2.2.2. On all products in Batch 3, the flux was applied above the rings and the solid filler material was used. No surface preparations were performed on the parts.

Batch 4 (Ex nr 31 - 40)
For Batch 4 different parameters were used. For Ex nr 31 - 35, Program 1_3 and solid filler material were used. On Ex nr 31 three rings were used to see the difference in visual appearance. For Ex nr 32 - 35 two rings were used, but here the flux was applied under the rings to see the difference in flux entrapped in the X-ray. For Ex nr 36 - 40 flux-integrated filler material was used. For Ex nr 36 Program 5 was used. To decrease the temperatures on the connections, Equation 3.6 was used to modify Program 5 to Program 5_1 for Ex nr 37. Further, Program 5_1 was modified to Program 5_2 in the same way for Ex nr 38. For Ex nr 39 Program 1_3 (program adapted to solid filler material) was used to see how the flux-integrated filler material behaved. For Ex nr 40 the product was brazed by manual brazing to see how the flux-integrated filler material behaved.

Batch 5 (Ex nr 41 - 50)
For Batch 5 Ex nr 41 - 45 solid filler material was used and for Ex nr 46 - 50 with flux-integrated filler was used. For the products with solid filler material, the flux was applied under the rings and in little amount. The used program was Program 1_4, modified from Program 1_3. Important to note is that Equation 3.6 was not used to adjust the heat curve to achieve a better results in a visual appearance on the joints. The change from Program 1_3 to Program 1_4 was free-formed by the author of this master's thesis. For Ex nr 46 was the flux-integrated filler used and for this was a new program formed, Program 3. This was also free formed by the author and not based on Equation 3.6. For Ex 47 - 50 was Program 3 used as based and different adjustments of Program 3 were used for Ex nr 46 - 50 and the programs created were Program 3_1 - 7. The goal was to achieve higher temperatures on the connections and joints.

Batch 6 (Ex nr 51 - 60)
For Batch 6 all products were used with flux-integrated filler material and induction program based on Program 3. Different adjustments of Program 3 was used for

Ex nr 51 - 60 and the programs created were Program 3_8 - 12. The goal was to adjust the heat curve to achieve a better results in a visual appearance on the joints.

Batch 7 (Ex nr 61 - 70)
For Batch 7 all products was used with flux-integrated filler material and induction program based on Program 3. Different adjustments of Program 3 was used for Ex nr 61 - 70 and the programs created were Program 3_13 - 18. The goal was to adjust the heat curve to achieve better result in visual appearance on the joints.

Batch 8 (Ex nr 71 - 80)
For Batch 8, Program 1_4 was used and both Mechanical nr 2 and Chemical surface preparations were performed. The purpose was to eliminate oxides and grease on the pipe and the fitting, to see if the formation of inclusions and bubbles changed in the joint, which could be seen in X-ray. On all products, in Batch 8 the flux was applied under the rings and with a little amount. The solid filler material was used.

Batch 9 (Ex nr 81 - 90)
For Batch 9, was Program 1_4 used, but no surface preparations were performed. This batch had the same parameters as Batch 8 and was set as a reference to the elimination of grease and oxides that was performed in Batch 8.

4

Results

This chapter describes the results of the investigation of the induction brazing process at the company and the results from the experimental study that investigated different process parameters for induction brazing of the circular pipes. The methodology of the investigation and the experimental part can be followed in Chapter 3.

4.1 Results from existing brazing process study

This section presents the results from the existing brazing process study at the company. It includes the investigation of the coils, the gaps for the connection, the required amount of filler material, and the formation of new induction machine programs.

4.1.1 Results of the investigation of the coils

During the investigation of the efficiency of the coil H1 and H2 for the induction machine, no visible difference in oxide formation around the pipe could be found. From the video recordings it could be observed that the formation of the oxides during the heat cycle, was even around the pipes and any cold spots from the coils could not be noticed. However, it could be noticed that the copper pipe reached brazing temperatures much faster than the fitting pipe of stainless steel, which can be explained by the 22 times higher thermal conductivity for copper compared to stainless steel, which can be seen in Table 3.1. Another important observation from the video recording was that the copper pipe "jumped" during the heat cycle of the brazing process.

Another observation during the investigation was that the maximum effect (power) of the induction machine was reached already at 72 % of the target set point for the current for the coils. Through conversations with the supplier of the induction machine, it was explained that the coils were adapted to the application and that 100 % target set point of the current was not necessary to reach maximum power.

4.1.2 Results for tolerances and gaps

By Equation 3.1, the gap is calculated from dimensions specified in the technical drawing of the connection, which is illustrated in Figure 4.1. The calculated values for the maximum and minimum values of the gap were 0.190 - 0.255 mm and 0.270 -

0.335 mm for connections NR3 respective NR4. The recommended gaps for capillary silver brazing, 0.050 - 0.200 mm from *Karlebo Handbook* for is also included in Figure 4.1 (Björklund et al., 2015).

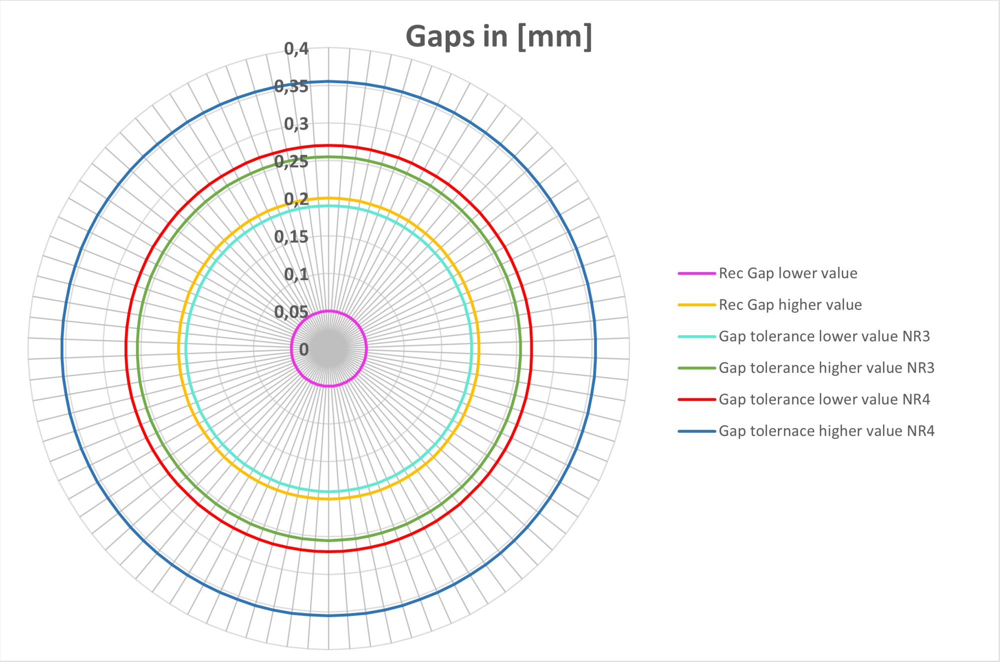

Figure 4.1: Illustration of recommended gap-range for the joint compared with gap-range for the maximum and the minimum gap that is calculated from the tolerances from the technical drawings for NR3 and NR4.

Figure 4.1 illustrates that the gap tolerances for connection NR4 are much larger than the recommended gaps for this type of application. Even the minimum gap for the NR4 is far away from the maximum recommended gap. Also, the gap tolerances for connection NR3 are much larger than recommended, but the minimum gap is just below the maximum recommended gap.

4.1.3 Results for amount of filler material

The recommended and used amount of solid filler material was two rings. For the flux-integrated filler the recommended amount were one ring. This was compared with Equation 3.2 that calculated the required amount of solid filler and the required amount of flux-integrated filler was calculated from a supplier. The results can be seen in Table 4.1, where also the average amount of solid filler material suitable for manual flame brazing with rods of the same connections. The calculated required volume for each connection gap is also presented in the table, calculated with 70 % joint filling of the total maximum joint length (15.6 mm).

Table 4.1: Used amount of filler material compared with required amount for the connections NR3 and NR4. Solid-, flux-integrated filler material and manual brazing with rods for the same application.

	NR3:	**NR4:**
Required amounts:	135.2 mm^3	112.8 mm^3
Used filler material:	**Amount:**	**Amount:**
Solid (2 rings)	192.1 mm^3	122.1 mm^3
	Compared with NR3:	**Compared with NR4:**
	42 % too much used	8 % too much used
Used filler material:	**Amount:**	**Amount:**
Flux-integrated (1 rings)	142.6 mm^3	90.1 mm^3
	Compared with NR3:	**Compared with NR4:**
	20 % too much used	10 % too less used
Used filler material:	**Amount:**	**Amount:**
Manual brazing (rods)	257.9 mm^3	144.7 mm^3
	Compared with NR3:	**Compared with NR4:**
	91 % too much used	28 % too much used

For the solid filler material it could be seen that the amount of two rings was enough for the application. For the flux-integrated filler, the amount is 10 % lower than the required amount for connection NR4. However, the design and amount of one ring of the flux-integrated filler did not make it possible to use two rings for this application. For the manual brazing, too much material was used for connection NR3. The reason for this could be that during the manual brazing, a joint edge was often created to improve the visual appearance of the joint.

4.1.4 Results for formulation of induction machine programs

With Equation 3.6, two programs that are adjusted to the solid filler material described in Table 3.2 was created. One program adjusted to the melting range of the filler material (called Program 1) and one program with a bit higher temperatures (called Program 2). Program 1 can be seen in Figure 4.2 and Program 2 can be seen in Figure. 4.3.

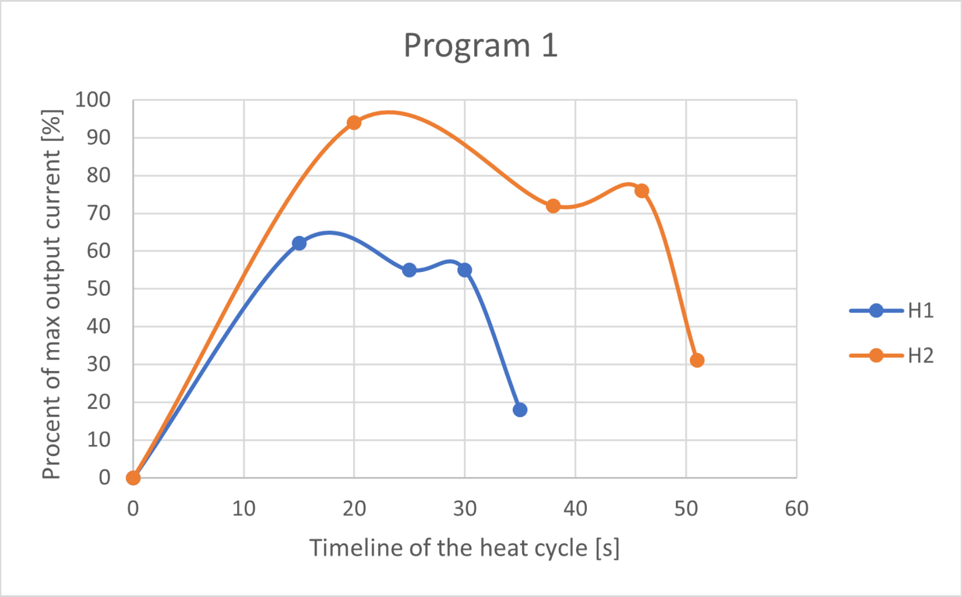

Figure 4.2: Illustration of induction machine Program 1 for coil H1 respectively H2.

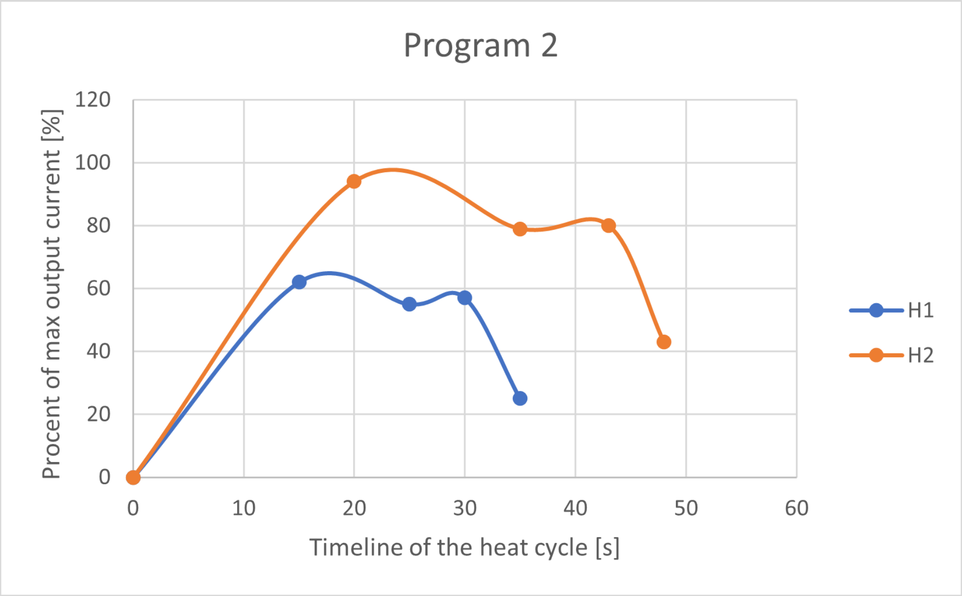

Figure 4.3: Illustration of induction machine Program 2 for coil H1 respectively H2.

With Equation 3.6, two programs adjusted to the flux-integrated filler material described in Table 3.2 were created. One program adjusted to the melting range of the filler material (called Program 5) and one program with a bit higher temperatures (called Program 6). Program 5 can be seen in Figure 4.4 and Program 6 can be seen in Figure 4.5.

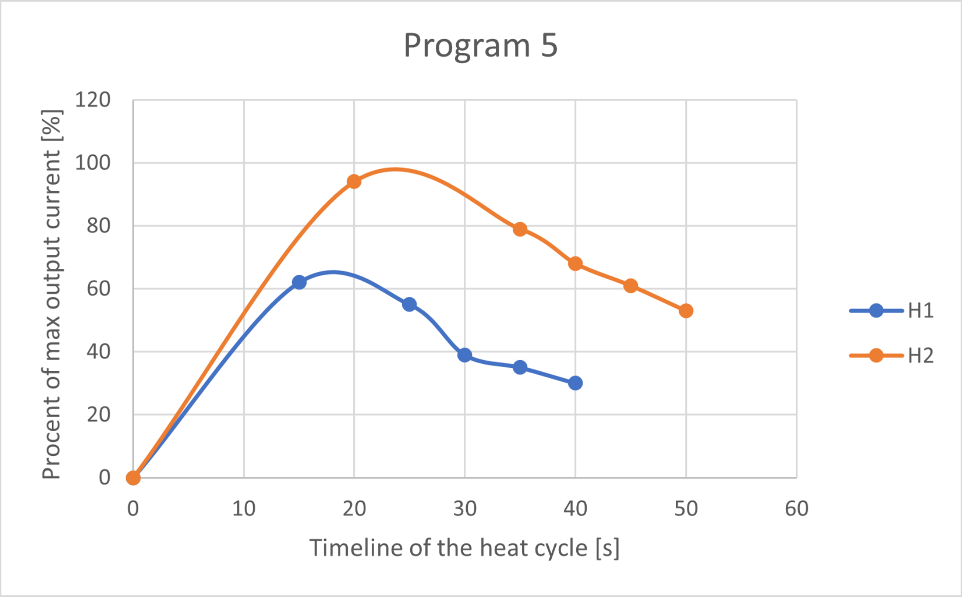

Figure 4.4: Illustration of induction machine Program 5 for coil H1 respectively H2.

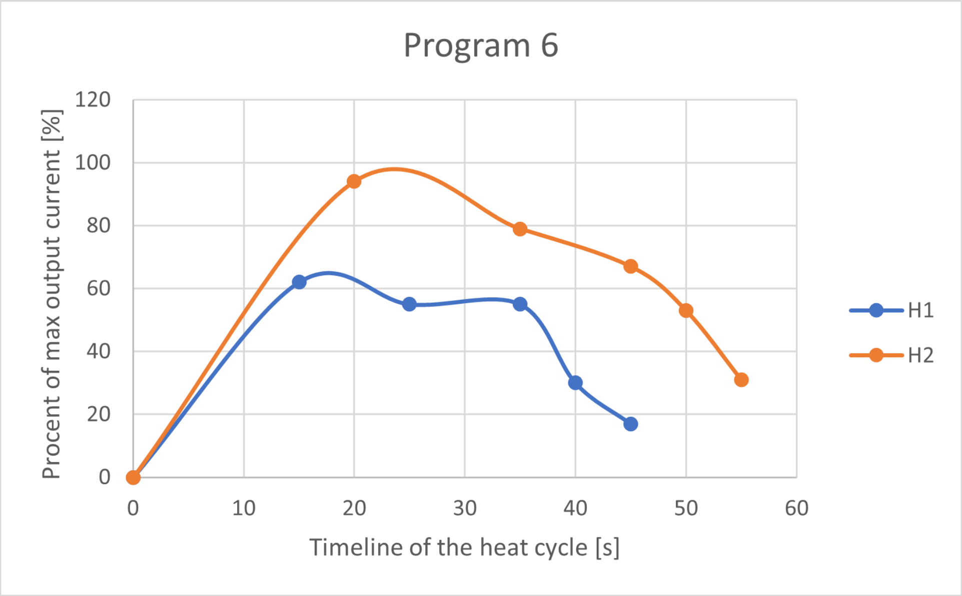

Figure 4.5: Illustration of induction machine Program 6 for coil H1 respectively H2.

Program 1, 2, 5, and 6 were used as the base for the experimental studies and the later modified programs, which can be seen in Appendix B and Appendix C.

4.2 Results from experimental study

This section presents the results from the investigations of the newly formulated programs and results from the experimental study where different parameters were changed. The section ends with a deeper investigation of the gaps from each batch during the experimental part.

4.2.1 Results for investigation of formulated induction machine programs

With help from the IR-thermometer, the reached temperature for Programs 1, 2, 5 and 6 were examined. For Program 2 and 6, which was created to add extra heat, the IR-thermometer showed temperatures over 800°C. This was too high for the used filler materials since they only had a working temperature of 650 - 710 °C for the solid filler material and 650 - 720 °C for the flux-integrated, which can be seen in Table 3.2. Therefore, Program 2 and 6 were not used during the experimental part. The measured temperatures for Program 1 and 5 can be seen in Figure 4.6 and 4.7.

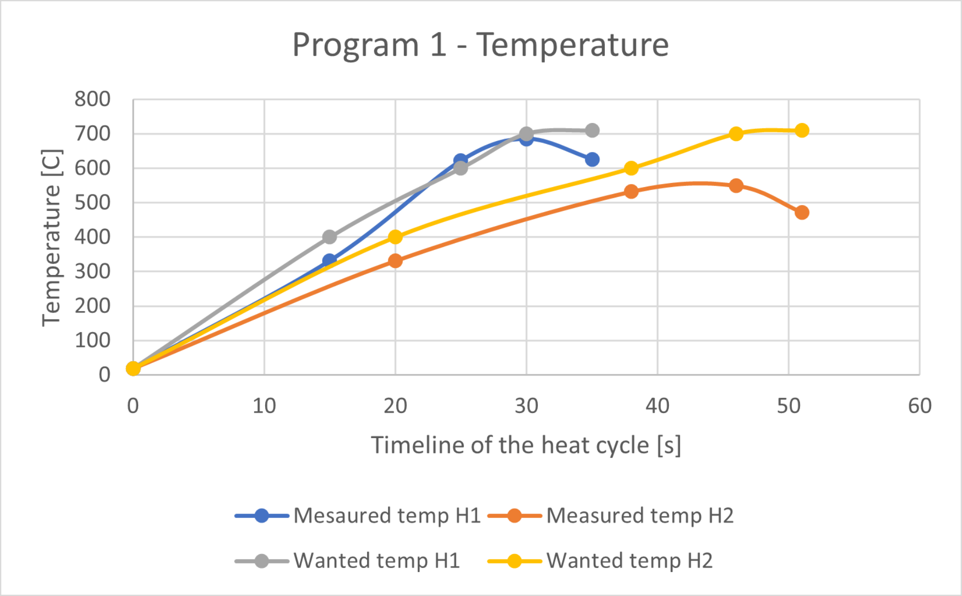

Figure 4.6: Illustration of temperature curve induction machine Program 1 for coil H1 respectively H2 compared with wanted temperature achieved for each segment of the program.

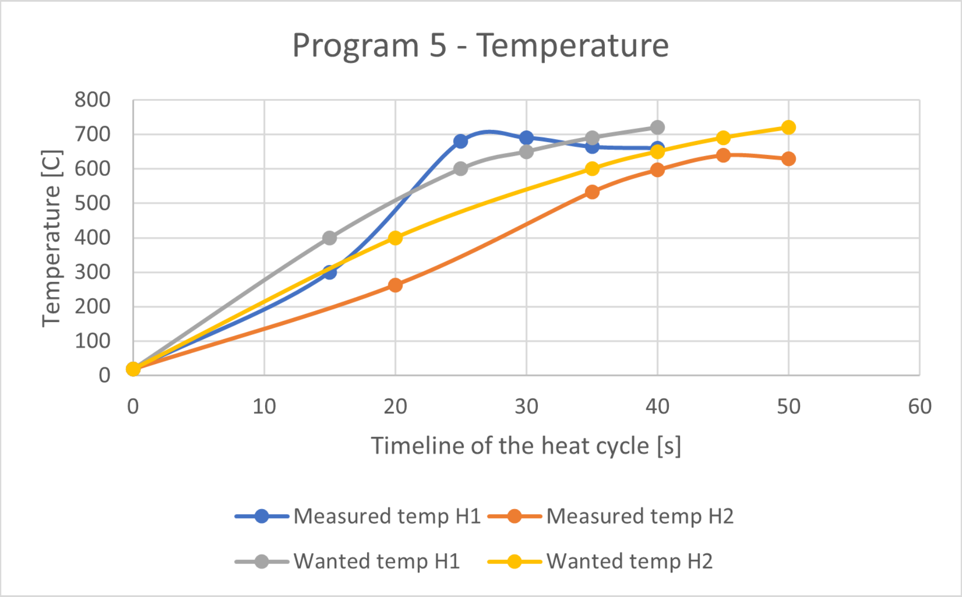

Figure 4.7: Illustration of temperature curve induction machine Program 5 for coil H1 respectively H2 compared with wanted temperature achieved for each segment of the program.

Programs 1 and 5, however, showed temperatures very close to what was strived for each segment and was therefore further used during the expressive study described in Chapter 3 and presented in Section 4.2.2. These programs were then modified during the experimental parts. Due to time limitations, not all programs was examined by the IR-thermometer. However, the programs that achieved the best visual appearance for respective filler material (for the solid and for the flux-integrated filler material) were examined and the temperature curves are presented below. The program that achieved the best visual appearance for the joint regarding the solid filler material was Program 1_4 and the temperature curve for the program can be seen in Figure 4.8.

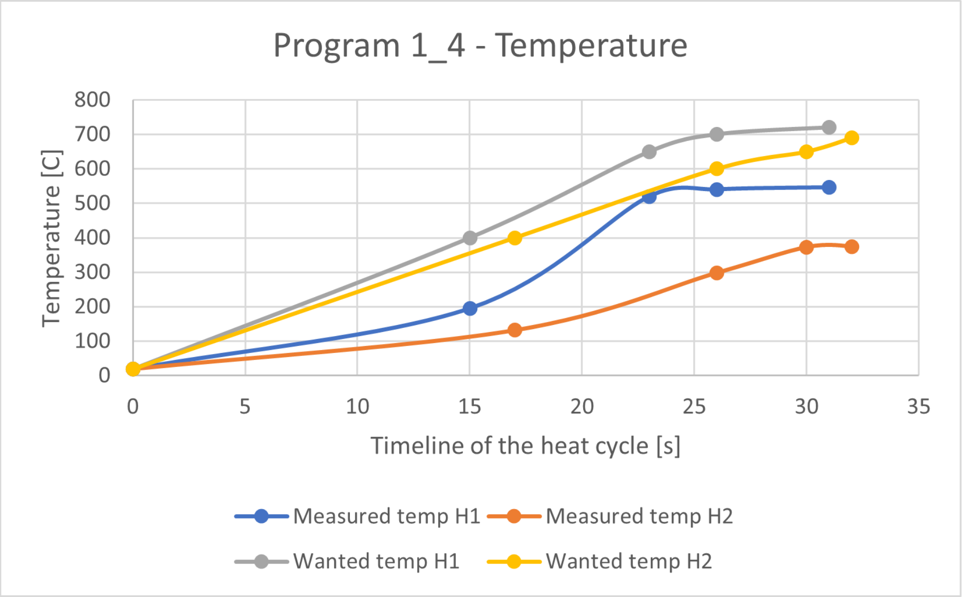

Figure 4.8: Illustration of temperature curve induction machine Program 1_4 for coil H1 respectively H2 compared with wanted temperature achieved for each segment of the program.

The program that achieved the best visual appearance for the joint regarding the flux-integrated filler material was Program 3_16 and the temperature curve for the program can be seen in Figure 4.9.

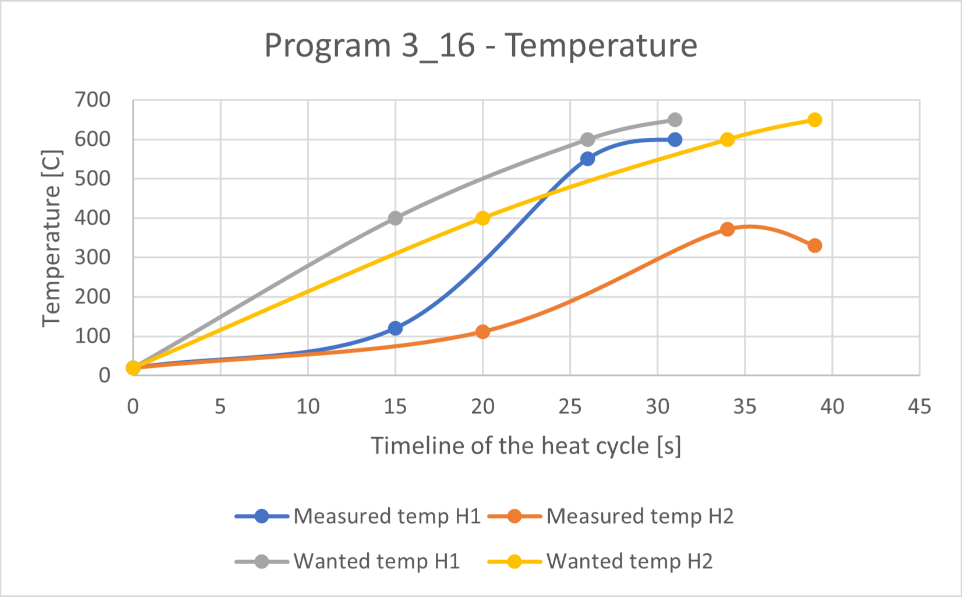

Figure 4.9: Illustration of temperature curve induction machine Program 3_16 for coil H1 respectively H2 compared with wanted temperature achieved for each segment of the program.

In Appendix C all the complete induction machine programs are stated in table-form. In Appendix B the same complete induction machine programs are presented in figure-form. The results of the experimental parts for the 90 products are presented in Section 4.2.2.

4.2.2 Results for the test of different process parameters

Below is a short description of the result of the induction brazing process for each batch and product (Ex nr), full detailed results for each connection, and X-ray results can be seen in Appendix D. Not all 90 products were sent to X-ray due to insufficiently satisfactory visual appearance of the joints. In total 77 out of 90 products were sent for X-ray, and 22 of these were blocked (meaning that the product can not be used for its end purpose).

Batch 1 (Ex nr 1 - 10)
For Batch 1, the five first products (Ex nr 1 - 5) were not sent to X-ray because of insufficient results on NR4 due to too high temperature and the filler material went too far down in the gap. For Ex nr 6 - 8, the program was adjusted but NR4 still had too high heat. For Ex nr 9 - 10 the program was adjusted further and the visual appearance became decent for both connections. On the X-ray, Ex nr 6 - 10 was on the limit on the joint filling and included both big and small voids and inclusions. The best Ex nr according to the X-ray for connection NR3 was Ex 7 and for NR4 was Ex 10. The assessment from the X-ray department was that connection NR3 has significantly more voids/inclusions and is mixed between large and small, while the NR4 connection has slightly larger voids/inclusions but significantly smaller in number, see Figure 4.10 and Figure 4.11. No difference in the mechanical surface

preparations on the joints could be noticed.

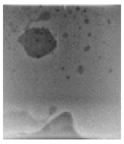

Figure 4.10: Illustration of X-ray for connection NR3 for Batch 1.

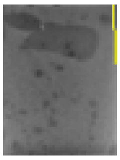

Figure 4.11: Illustration of X-ray for connection NR4 for Batch 1.

Batch 2 (Ex nr 11 - 20)

For Batch 2, all products had a decent visual appearance for both connections. On the X-ray, the joints were not on the limit for the joint filling as in Batch 1. However, they still contained voids and inclusions, but to a lesser extent. The best Ex nr according to the X-ray for connection NR3 was Ex 15 and for NR4 was Ex 17. The assessment from the X-ray department was that the NR4 connection in particular improved in Batch 2 compared to Batch 3 regarding voids and gas pockets, see Figure 4.12 and Figure 4.13. A small difference in the result could be noticed and the cause was probably the mechanical surface preparations.

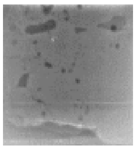

Figure 4.12: Illustration of X-ray for connection NR3 for Batch 2.

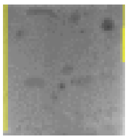

Figure 4.13: Illustration of X-ray for connection NR4 for Batch 2.

Batch 3 (Ex nr 21 - 30)

For Batch 3, all products had decent visual appearance for both connections but the program was changed to slow the solidification and less flux was used to reduce the risk for entrapped flux in the joints and brushed under the rings. The best Ex nr according to the X-ray for connection NR3 was Ex 30 and for NR4 was Ex 26. The assessment from the X-ray department was that there are still voids/inclusions and very large ones in many of the connections, but significantly fewer of the smaller voids/inclusions, see Figure 4.14 and Figure 4.15. A small difference in the result could be noticed and the cause could be the less amount of flux used and how the flux was applied under the rings.

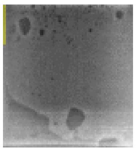

Figure 4.14: Illustration of X-ray for connection NR3 for Batch 3.

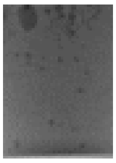

Figure 4.15: Illustration of X-ray for connection NR4 for Batch 3.

Batch 4 (Ex nr 31 - 40)

For Batch 4, different parameters were used and all products (Ex 31 - 35) with solid filler material had a decent visual appearance for both connections, except Nr 31 where three rings were used and filler material ran over. The new program for the solid filler had both a visually better appearance and better performance on the X-ray results. The assessment from the X-ray department was that the filler flows down well into the capillary, but there are still voids, both large and small, even if the large ones have decreased slightly. The best Ex nr according to the X-ray for connection NR3 was Ex 32 and for NR4 was Ex 33. For the products with flux-integrated filler (Ex nr 36 - 40) no joints were visually approved, see Figure 4.16 and Figure 4.17. The program for the flux-integrated had to high temperature which caused the filler to flow too far down in the joint. The manually brazed Ex nr 40 with the flux-integrated did not behave well under the manual brazing.

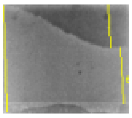

Figure 4.16: Illustration of X-ray for connection NR3 for Batch 4 for the flux-integrated filler material.

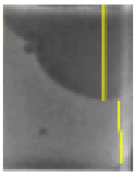

Figure 4.17: Illustration of X-ray for connection NR4 for Batch 4 for the flux-integrated filler material.

Batch 5 (Ex nr 41 - 50)

For Batch 5, different parameters were used and all products (Ex 41 - 45) with solid filler material had decent visual appearance for both connections. The new program for the solid filler compared with Batch 3 had a little better visual appearance, but similar performance on the X-ray results, but still voids, see Figure 4.18 and Figure 4.19. The best Ex nr according to the X-ray for connection NR3 was Ex 41 and for NR4 was Ex 41. For the products with flux-integrated filler (Ex nr 46 - 50), no joints were visually approved due to the new program that was free-formed by the author. More heat was needed.

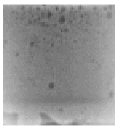

Figure 4.18: Illustration of X-ray for connection NR3 for Batch 5 for the solid filler material.

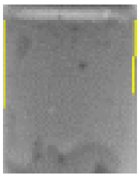

Figure 4.19: Illustration of X-ray for connection NR4 for Batch 5 for the solid filler material.

Batch 6 (Ex nr 51 - 60)

For Batch 6, all products had flux-integrated filler material. No approved visual joints or X-rays. Batch 6 was used to formulate a program that produced approved visual approved joints. The best Ex nr according to the X-ray for connection NR3 was Ex 55 and for NR4 was Ex 56. Still a lot of cavities and unsatisfactory joint filling. More adjustments were required of the program to obtain visually approved joints.

Batch 7 (Ex nr 61 - 70)

For Batch 7, all products had flux-integrated filler material. Batch 7 was also used to formulate a program that produced visually approved joints. Best visual approved joints were produced by Program 3_16. The best Ex nr according to the X-ray for connection NR3 was Ex 55 and for NR4 was Ex 56. Still a lot of cavities and unsatisfactory joint filling, see Figure 4.20 and Figure 4.21. It was decided not to use the flux-integrated filler material due to too much uneven result was achieved, even if a decent visual appearance was achieved.

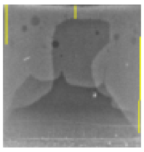

Figure 4.20: Illustration of X-ray for connection NR3 for Batch 7 for the flux-integrated filler material.

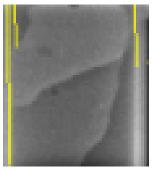

Figure 4.21: Illustration of X-ray for connection NR4 for Batch 7 for the flux-integrated filler material.

Batch 8 (Ex nr 71 - 80)

For Batch 8, Program 1_4 was used and mechanical nr 2 surface preparations were performed on all products as well as chemical surface preparations. All products had a good visual appearance for both connections. The flux was brushed under the rings. The best Ex nr according to the X-ray for connection NR3 was Ex 72 and for NR4 was Ex 74. The assessment from the X-ray department was that there are still voids and large cavities and that the filler material flows to different depths around the connections. The gaps for the connection were very varied and occasional connection had inserts (pipes) that were skew, which blocked filler from flow, see Figure 4.22 and Figure 4.23. No evident difference could be noticed in the X-ray results regarding the voids, even with the carefully done preparation of the surfaces. The skew insert was an indication that the pipe is not centered in the fitting pipe.

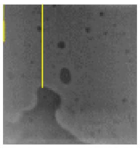

Figure 4.22: Illustration of X-ray for connection NR3 for Batch 8.

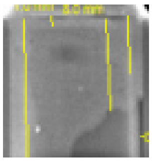

Figure 4.23: Illustration of X-ray for connection NR4 for Batch 8 with skew insert blocking filler material on one side.

Batch 9 (Ex nr 81 - 90)

For Batch 9, Program 1_4 was used, but no surface preparations were performed.

This batch had the same parameters as Batch 8 and was set as a reference to the elimination of grease and oxides that was performed in Batch 8. All products had good visual appearance for both connections. The flux was brushed under the rings. The best Ex nr according to the X-ray for connection NR3 was Ex 86 and for NR4 was Ex 83. The assessment from the X-ray department was that there are still voids and large cavities, but the NR4 connection is worse than NR3. Large gaps and oblique inserts are observed. Occasional connection had inserts that was skew that block filler from flow, see Figure 4.24 and Figure 4.25. No evident difference could be noticed between Batch 9 and Batch 8 of the X-rays result regarding the voids, even with the careful preparation of the surfaces in Batch 8.

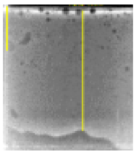

Figure 4.24: Illustration of X-ray for connection NR3 for Batch 9.

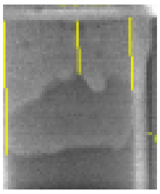

Figure 4.25: Illustration of X-ray for connection NR4 for Batch 9.

4.2.3 Results for measured gaps compared with result from X-ray

Each product pipes was measured as described in Chapter 3. The results of the measurements are illustrated in Figure 4.26 compared with the maximum and minimum gap calculated from the technical drawings, 0.190 - 0.255 mm and 0.270 - 0.335 mm for connections NR3 respective NR4. The recommended gaps for capillary induction silver brazing, 0.050 - 0.200 mm (Björklund et al., 2015), are also included in Figure 4.26.

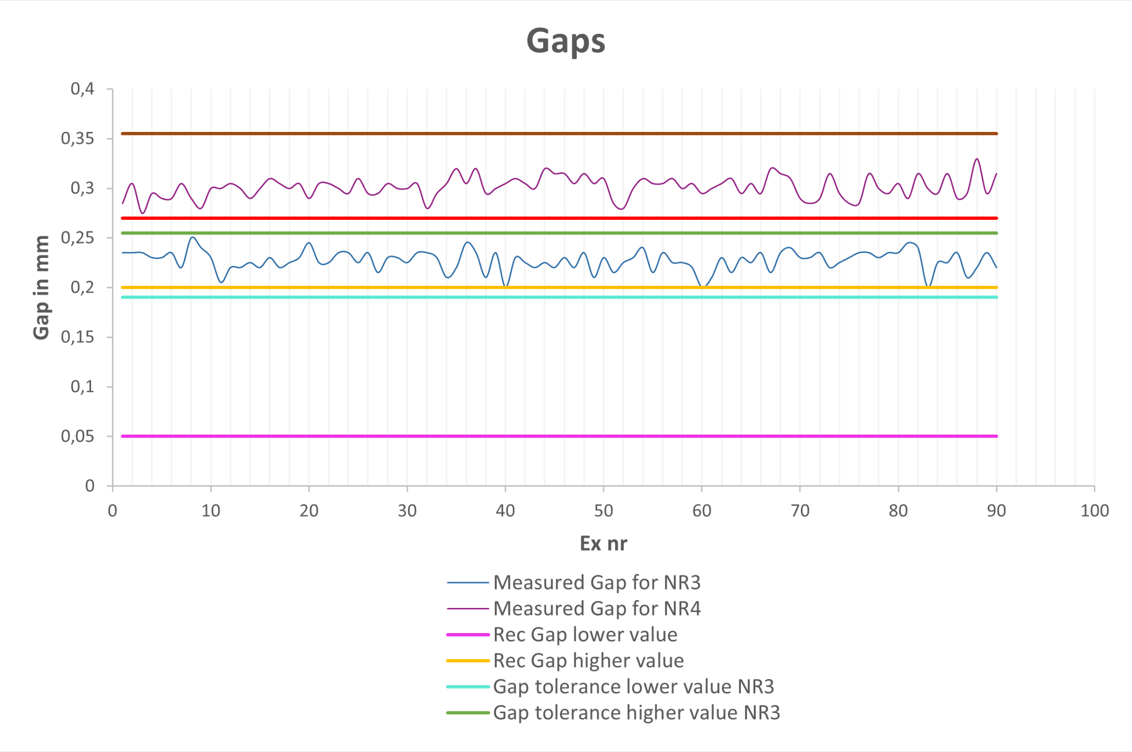

Figure 4.26: Illustration of measured gaps for connections NR3 and NR4 for each product (Ex nr 1 - 70) during the experimental study. Lines for recommended gap range for the joint are marked in the figure. Lines for gap-range for the maximum and the minimum gap is marked in the figure and is calculated from the tolerances from the technical drawings for NR3 and NR4.

In Figure 4.26 it can be seen that all of the 90 products included in the test plan are inside the tolerances, but also that the gaps are above the recommended gaps for brazing applications with silver filler materials which are also presented in Figure 4.1. I Figure 4.27 to Figure 4.35 the gaps for each batch are presented together with the gap for the best Ex nr for each connection (NR3 and NR4) according to the X-ray result. Also the blocked connection according to the X-ray result is presented.

Batch 1 (Ex nr 1 - 10)

See Figure 4.27. The average value of the gap was 0.234 mm for NR3 and 0.292 mm for NR4. Here it can be seen that no products were blocked and from calculations, it can be seen that the best joint for NR3 was about 6 % below the average gap for connection NR3. For NR4 the best joint was about 3 % above the average gap for connection NR4.

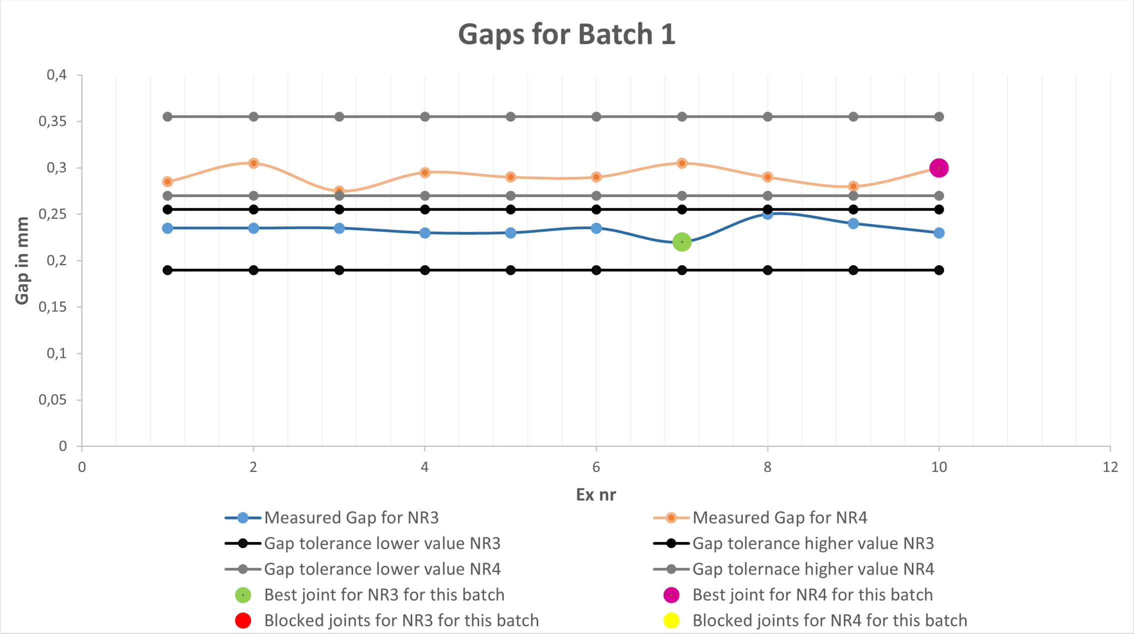

Figure 4.27: Illustration of gaps for Batch 1.

Batch 2 (Ex nr 11 - 20)

See Figure 4.28. The average value of the gap was 0.224 mm for NR3 and 0.301 mm for NR4. Here it can be seen that no products was blocked and from calculations it can be seen that the best joint for NR3 was about 2 % below the average gap for connection NR3. For NR4 was the best joint about 1.5 % above the average gap for connection NR4.

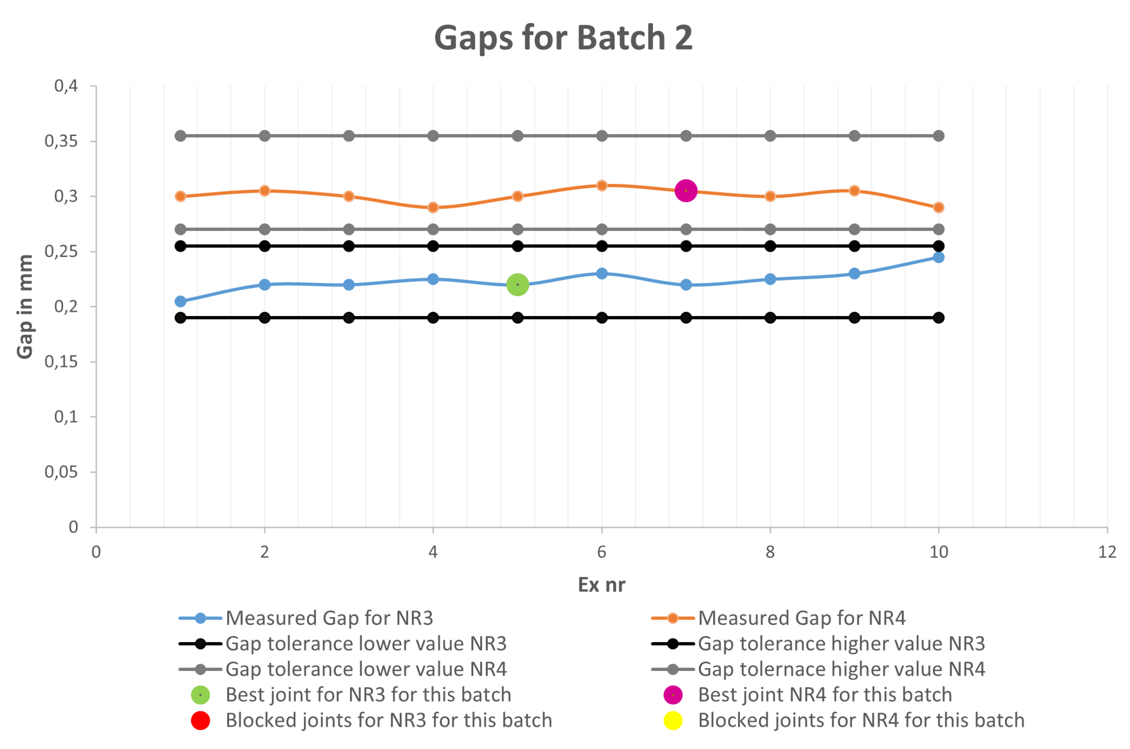

Figure 4.28: Illustration of gaps for Batch 2.

Batch 3 (Ex nr 21 - 30)

See Figure 4.29. The average value of the gap was 0.228 mm for NR3 and 0.301 mm for NR4. Here it can be seen that no products was blocked and from calculations it can be seen that the best joint for NR3 was about 1.5 % below the average gap for connection NR3. For NR4 the best joint was about 2 % below the average gap for connection NR4.

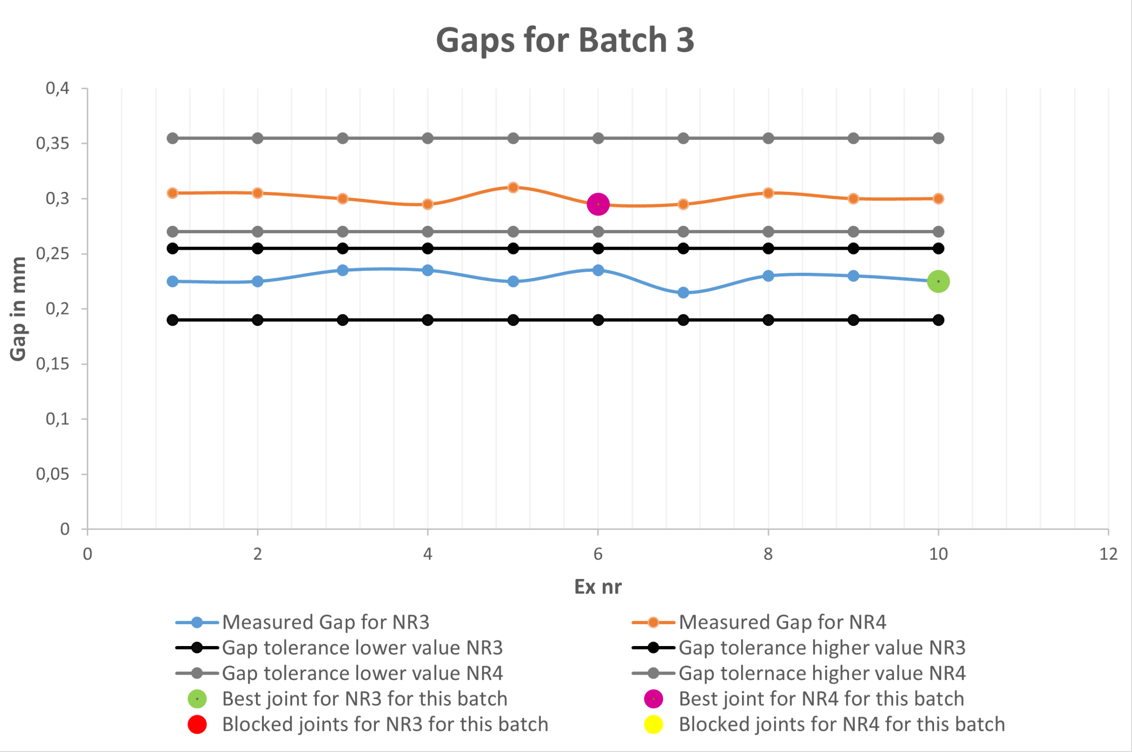

Figure 4.29: Illustration of gaps for Batch 3.

Batch 4 (Ex nr 31 - 40)
See Figure 4.30. The average value of the gap was 0.223 mm for NR3 and 0.303 mm for NR4. Here it can be seen that some of the products were blocked and from calculations it can be seen that the best joint for NR3 was about 4 % over the average gap for connection NR3. For NR4 the best joint was about 2.5 % below the average gap for connection NR4. For the gaps for the blocked connections NR3, they were equal to the average gap for connection NR3. For the blocked NR4 gaps they were about 0.5 % above the average gap for connection NR4.

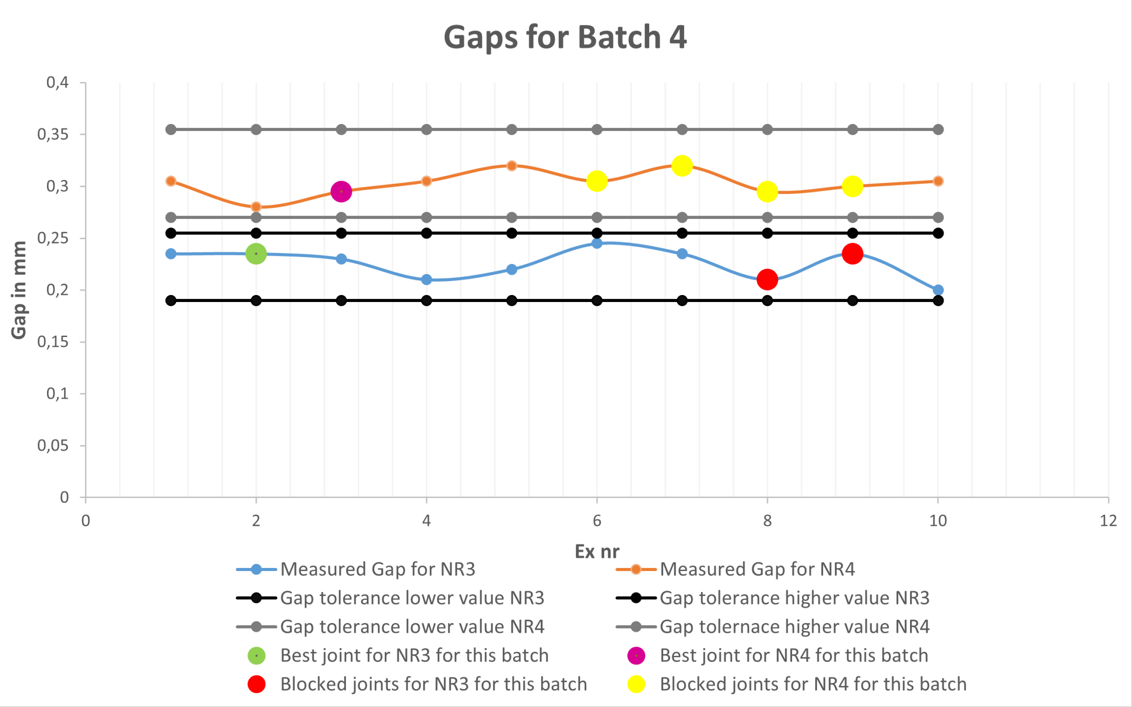

Figure 4.30: Illustration of gaps for Batch 4.

Batch 5 (Ex nr 41 - 50)
See Figure 4.31. The average value of the gap was 0.225 mm for NR3 and 0.310 mm for NR4. Here it can be seen that some of the products were blocked and from calculations it can be seen that the best joint for NR3 was about 2.5 % above the average gap for connection NR3. For NR4 the best joint was similar to the average gap for connection NR4. For the gaps for the blocked connections NR3, they were about 1.5 % above the average gap for connection NR3. For the blocked NR4 gaps they were about 0.5 % below the average gap for connection NR4.

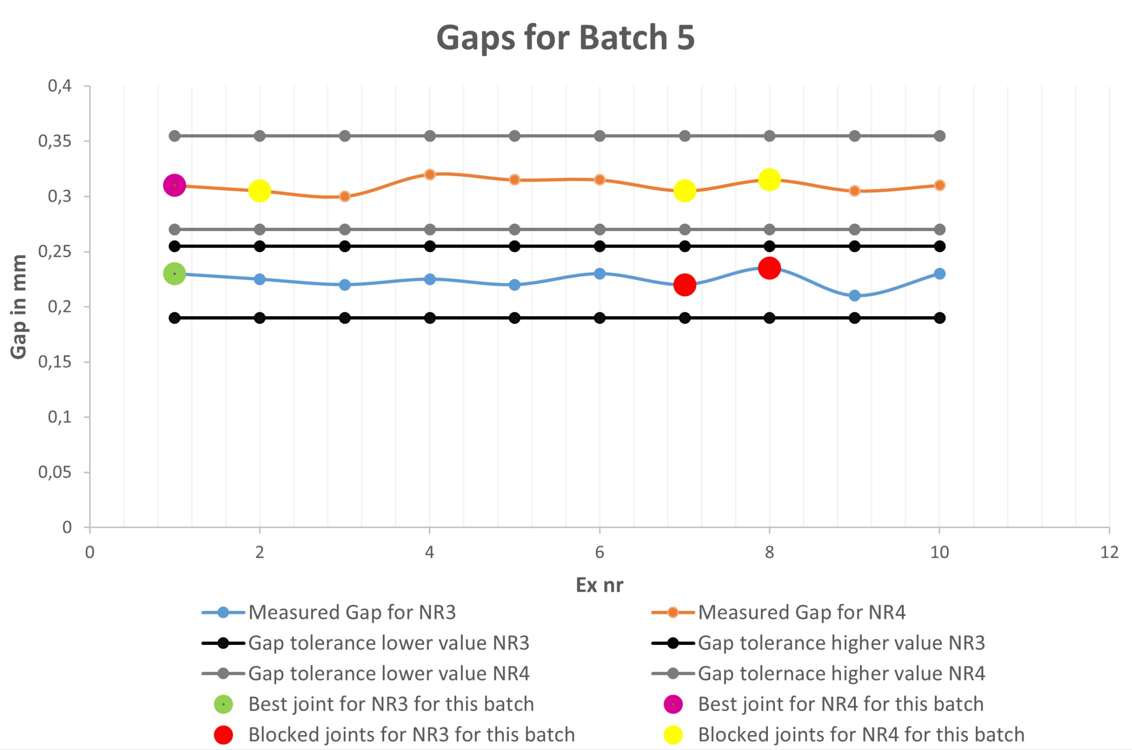

Figure 4.31: Illustration of gaps for Batch 5.

Batch 6 (Ex nr 51 - 60)

See Figure 4.32. The average value of the gap was 0.233 mm for NR3 and 0.300 mm for NR4. Here it can be seen that some of the products was blocked and from calculations it can be seen that the best joint for NR3 was about 4 % below the average gap for connection NR3 for this batch. For NR4 the best joint was about 2 % over the average gap for connection NR4. For the gaps for the blocked connections NR3, they were about 1.5 % below the average gap for connection NR3. For the blocked NR4 gaps they were about 1 % over the average gap for connection NR4.

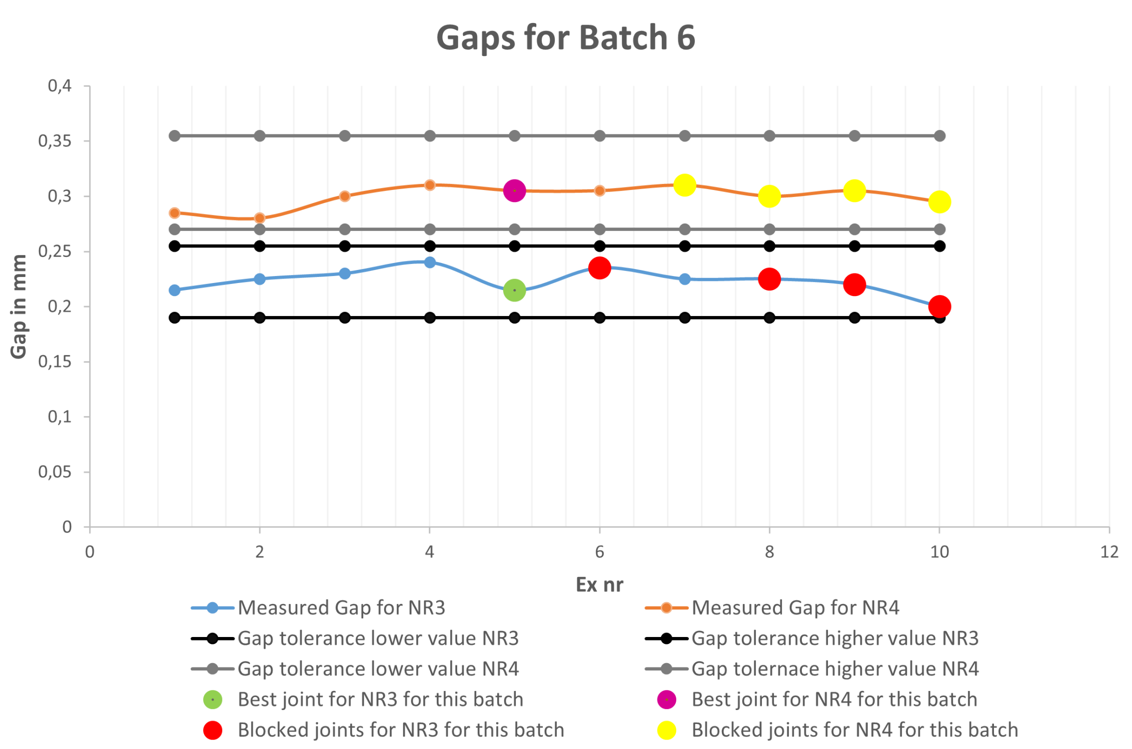

Figure 4.32: Illustration of gaps for Batch 6.

Batch 7 (Ex nr 61 - 70)
See Figure 4.33. The average value of the gap was 0.227 mm for NR3 and 0.305 mm for NR4. Here it can be seen that some of the products was blocked and from calculations it can be seen that the best joint for NR3 was about 1.5 % over the average gap for connection NR3. For NR4 the best joint was about 3 % below the average gap for connection NR4 for this batch. For the gaps for the blocked connections NR3 they were about 0.5 % below the average gap for connection NR3. For the blocked NR4 gaps they were about similar to the average gap for connection NR4.

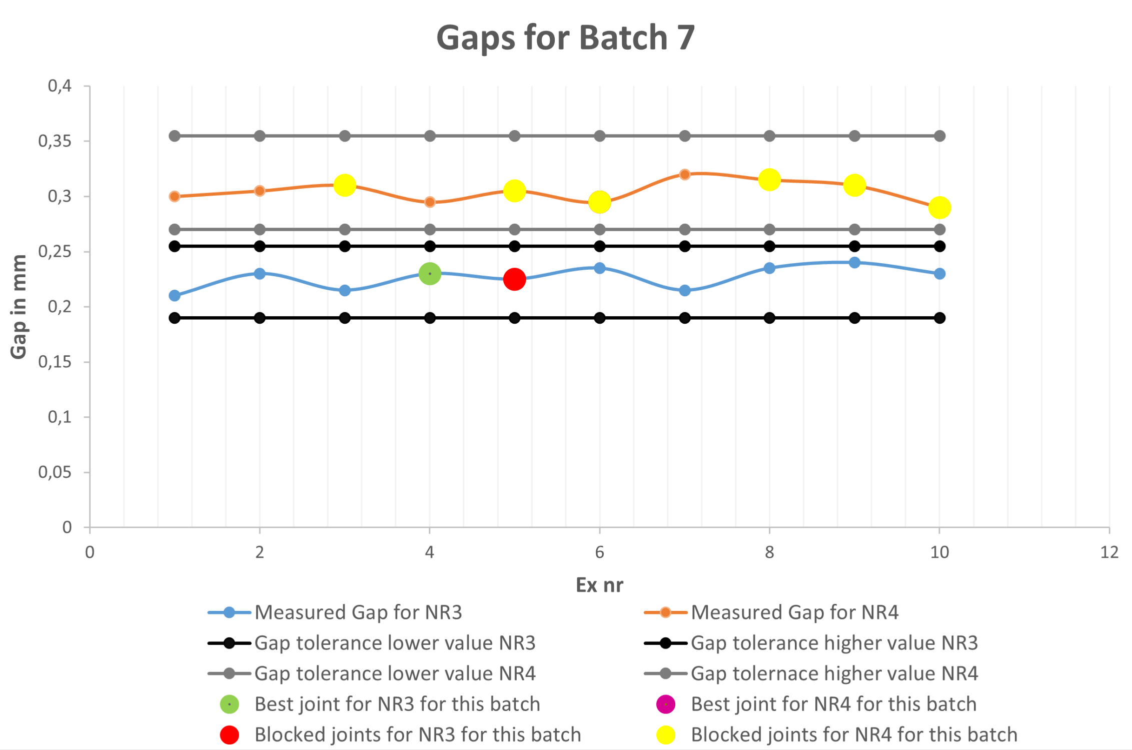

Figure 4.33: Illustration of gaps for Batch 7.

Batch 8 (Ex nr 71 - 80)
See Figure 4.34. The average value of the gap was 0.231 mm for NR3 and 0.297 mm for NR4. Here it can be seen that some of the NR4 connections were blocked and from calculations it can be seen that the best joint for NR3 was about 2 % above the average gap for connection NR3. For NR4 the best joint was about 0.5 % below the average gap for connection NR4. For the blocked NR4 gaps they were about similar to the average gap for connection NR4.

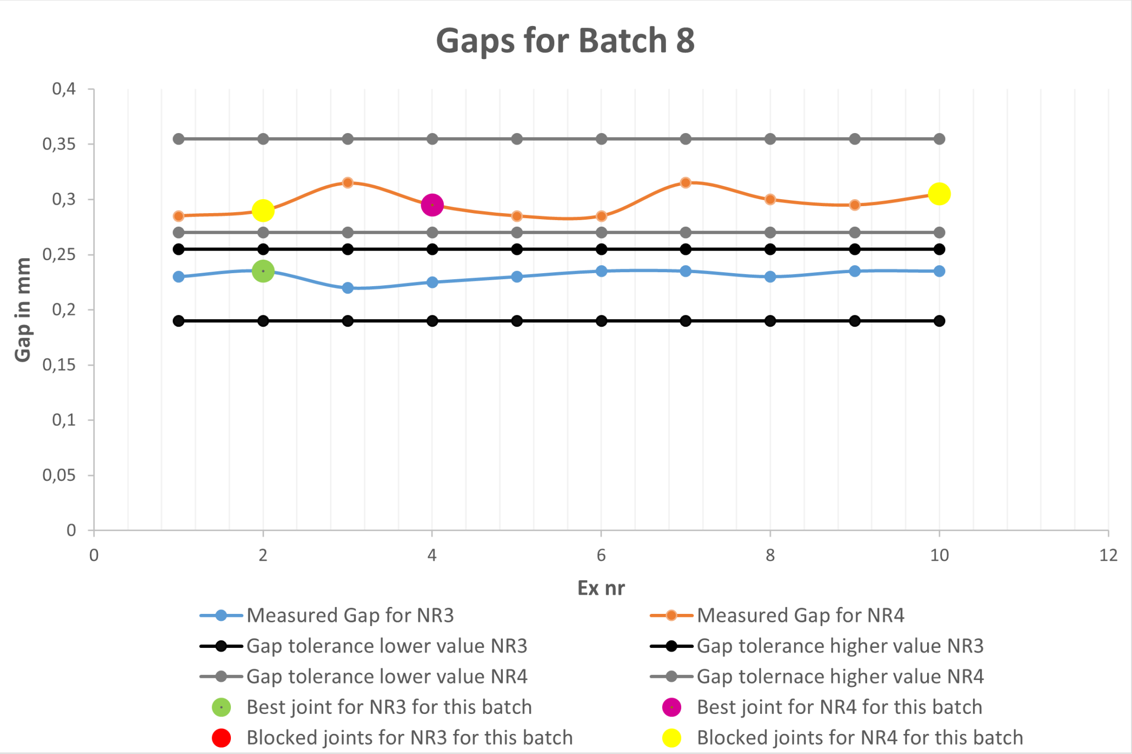

Figure 4.34: Illustration of gaps for Batch 8.

Batch 9 (Ex nr 81 - 90)
See Figure 4.35. The average value of the gap was 0.226 mm for NR3 and 0.304 mm for NR4. Here it can be seen that some of the products were blocked and from calculations it can be seen that the best joint for NR3 was about 4 % over the average gap for connection NR3. For NR4 the best joint was about 1.5 % below the average gap for connection NR4. For the gaps for the blocked connections NR3, they were about 7 % below the average gap for connection NR3. For the blocked NR4 gaps they were about 3 % below the average gap for connection NR4.

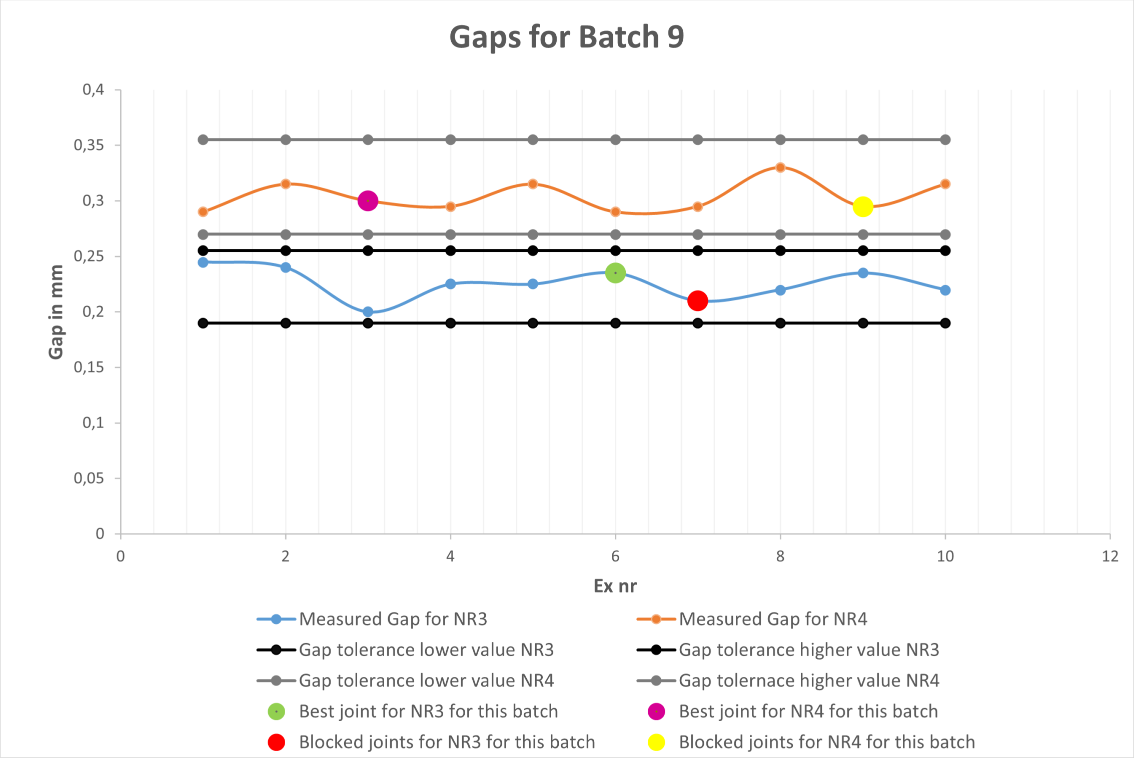

Figure 4.35: Illustration of gaps for Batch 9.

To summarize, at the current design are the joint gap between 0.190 - 0.255 mm according to calculations from the technical drawings for connection NR3. For NR4 at the current design is the joint gap between 0.270 - 0.335 mm. From the data from the measured gaps from the experimental test was the overall average value of the gap for NR3 0.227 mm. For NR4 was the average 0.301 mm. The average gap for the best joints for NR3 according to the X-ray department was 0.227 mm, which is equal to the overall average for NR3. The average gap for the best joints for NR4 according to the X-ray department was 0.300 mm, which is 0.3 % below the overall average for NR4. The average gap for the blocked joints for NR3 according to the X-ray department was 0.222 mm, which is 2.5 % below the overall average for NR3. The average gap for the blocked joints for NR4 according to the X-ray department was 0.304 mm, which is 0,8 % above the overall average for NR4. Detailed results for the measured gap for each connection from Batch 1 - 9 can be seen in Appendix D.

5

Discussion

In this chapter is the result presented in Chapter 4 discussed and compared with relevant theory from Chapter 2. Influential parameters for the induction brazing process at the company is discussed and the research questions establish at the beginning of this master's thesis in Chapter 1, are answered. At the end of this chapter are recommendations for the induction brazing station presented and suggestions for further studies are also presented.

5.1 Summary of the brazing process study

This section will discuss the results from the existing brazing process study performed at the company. When it comes to the investigation of the efficiency of the coils for the induction machine was there a suspected risk that the U-shaped coils would create so could "cold spots". However, from the investigation could no visible difference of oxide formation be seen around the pipes of the connections NR3 and NR4. Theoretically, there would be "cold" spots from the shape of the coil, where the coil does not reach around the pipes. However this was not the case for this application. One reason for this is could be that heat was conducted fast in the pipes, especially in the copper pipe with high thermal conductivity. This distribution of heat in the material inside the pipes eliminated probably the effect of "cold" spots for this application. Another reason for the none visible difference of oxide formation was that the coils were well adapted to the application, due to only 72 % target setpoint was needed to achieve maximum effect. A contributing factor to the well adapted coils is probably the amplifier on the sides of the coils, which contribute to the electromagnetic field acting on the workpiece. This will likely induce heat in the pipes in a sufficient way. In other words could the design of the coils be excluded as a main influential parameter for the unfilled quality requirement of the joints carried out at the induction brazing station.

According to the theory described in Section 2.2.5 is the design of the joint an important factor to achieve sound joints with brazing. The gap of the joint itself is one of the most influencing factors for the result of the joint. The gap affects defects like the formation of voids and other inter-metallic inclusions in the solidified joint gap, but also the force of the capillary action of the molten filler material during the brazing process. When analysing the result from the tolerances and gaps for connections NR3 and NR4 in Section 4.1.2 can it be seen that the calculated values for the maximum and minimum values of the gap was 0.190 - 0.255 mm and 0.270

- 0.335 mm for connections NR3 respective NR4. The recommended gaps for capillary silver brazing however 0.050 - 0.200 mm. When it comes to automated brazing methods like induction brazing are the recommended gaps are between 0.050 - 0.130 mm, but acceptable for gaps up to a maximum 0.200 mm. Here can it be seen that gap especially connection NR4 is considerably larger than recommended. This can be seen during the experimental part of this master's thesis where the vast majority of blocked connection is NR4. This is also something that is reflected in the X-ray results. According to the X-ray department connection NR4 is worse than NR3 when it comes to voids and other cavities inside the joints. Connection NR3 is on the limit to the recommended gap width, however from the experimental part could it be seen that the average gap for NR3 was 0.227 mm and all of the connections brazed included voids in a more or less amount. Connection NR3 and NR4 is temporarily manually brazed at the company and when examining this manually brazed connections through X-ray the joints are homogeneous and has more or less absences of voids and inclusions. One reason for this can be seen in Figure 2.10 in Section 2.2.5. Here can it been seen that for gap brazing performed with manually brazing with flux that the recommended gap width can be up to 0.5 mm.

Another observation by the X-ray department is skew copper pipes inside the stainless steel fitting pipe, especially on NR4 connection. This is something that also could be seen in the video recording from the investigation of the efficiency of the coils. There was the brazing cycle performed without the pre-placed filler material rings and here could it be seen that occasionally the copper pipe "jumped" during the heat cycle. This was probably due to the thermal expansion of the materials. However worth mentioning are that the stainless steel fitting pipe and the copper pipe have similar thermal expansion values, which could be seen in Table 3.1 in Section 3. This suggests that the centering of the copper pipe is a problem. This can also be seen in the technical drawings, no chamfers or similar solutions can be seen to center the pipe during the brazing process. The problem that has been seen by the X-ray department is that the skew pipes leaning to one side of the copper pipe and blocked in this way filler material to flow down in the joint on this side. This will lead to improper filling of the joint. A solution for lack of centering of the stainless steel fitting pipe, could as previously mentioned, be fixtures or to design the fitting pipe with chamfers to center the pipe right. Worth mentioning is that to properly examine the centering of the copper pipes from the experimental part should destructive sampling be carried out, which was not possible for this project.

When it comes to the results about the amount of filler material required compared to the used amount for the solid rings pre-placed for the induction brazing, compared to manual brazing with rods, can it be seen that significantly more amount of filler material is used in manual brazing, see Table 4.1. One reason for this can be that at the manual brazing is a joint edge created on top of the joint to make a better visual appearance, which causes more filler material to be consumed. However, another reason for the additional consumed amount of material for manual brazing is just because it is applied manually and the operator can see where more material is required during the brazing operation. This is also something that is reflected in when the joints are X-rayed as mentioned before, the joints are homogeneously when brazed manually with flame. Compared to induction brazing with pre-forms like rings, are the amount set before the operation begins, and the amount of filler material can not be adjusted to the specific gap for the specific joint brazed.

When it comes to the formulation of the induction machine programs, there is some uncertainty regarding the method used. Especially, with the measurements with the IR-thermometer:

- The IR-thermometer is a handheld tool. A fixture was built to eliminate some of the human factors regarding movements etc.
- The accuracy of the measurements is low due to the same distance to the joint to the IR-thermometer for each measurement was not the same. It was also hard to have the focus of the IR-thermometer on the right target position on the joint measured.
- The emission factor that was adjusted to the application on the thermometer was a middle value between the emission factor for copper and stainless steel. Worth mentioning is that the emission factor changes with temperature and is dependent on surface conditions for the measured surface on the joint. This in itself creates uncertainty in the measurements.

The equations used to form the induction machine programs, Equation 3.3 to 3.5, also has some sources of error to the results of this master's thesis project. The formulas were based on estimations and can be used as rough tools for estimating target points for the induction machine programs to reach certain temperatures for the brazed joints. However, these can be seen as sufficient when creating new programs for the induction brazing station, due to adjustments of the programs can be done through examination with visual and X-ray inspections to be able to achieve sound joints. This was something that was done to achieve the best visual appearance when it comes to Program 1_4 that produced the most satisfying visual joints for the solid filler material. The values for efficiency and resistance to the coil is also dependent on these specific connections NR3 and NR4, but also the specific filler material used. This could be seen in Program 5 and 6 that was created for the flux-integrated filler material. Here was the temperature to high, due to the programs were based on calculations with the solid filler material used at this project, and Program 4 was the current program at the beginning of this master's thesis project.

5.2 Summary of the experimental study

This section will discuss the results from the experimental study performed at the company. When it comes to the investigation of the formulated induction machine programs and the temperature profiles for the programs can it be seen that these curves, for example, see Figure 4.6 to 4.9, differs from the ideal heat cycle presented in Figure 2.11 in Section 2. The risk with this is that the flux or the filler material does not melt properly etc. However, through visual observations during the brazing cycle of joints with programs that produce satisfying visual joints, could it be seen that the flux was melted and activated before the filler material was melted. The temperature profiles are also dependent on the measurement of the IR-thermometer mentioned in the section above.

When it comes to tests of different parameters for the brazed connection NR3 and NR4 could it be seen despite all different parameters used, could still voids and inclusions in more or less quantity be seen in all products tested. The experimental part was performed alongside the theoretical study. Through the theoretical study could different potential affecting parameters be found. This theory was then tested through the experimental part of this project. The main parameters tested were:

- The heat profile through different programs.
- Two different filler materials.
- The way and amount of the flux was applied on the joints.
- Different surface preparations on the base materials.

The aim of the different heat profiles that were experimented, was to achieve approved visual joints, but also to raise the viscosity of the filler material during the molten phase. The importance of the viscosity for brazing was described in Section 2.2.3. The higher temperature of the melted filler material will theoretically lower viscosity. This in turn will improve the performance of the flow and the formation of the metallurgical bonds in the joints. However to summarize the different heat profiles could the results from the X-ray reports with the adjusted induction machine programs show no clear improvement regarding voids and other inclusions, regarding the connections with visual approved joints.

When it comes to the different filler materials tested was the results that the flux-integrated filler material did not work for this application. Reasons for this could be many. First of all, could the heat cycles related to the programs adjusted to the flux-integrated filler material be unfavorable. However program 3_16 produced decently approved visually joints but still showed a poor flow of the filler material inside the joint and the joints had not enough joint filling and included voids. Another reason could be that the joint gap is not adjusted to induction brazing and did not provide the right conditions for the capillary force that is required to fill the joint. The solid filler material used performed for the most part visually approved joints. The X-ray results of the solid filler material showed results that were inside the frame of the brazing standard, however voids and inclusions were still presented. The reason for this could be that the gap is not adjusted to induction brazing, due to what was described in Section 2.2.5. The gap is the most influencing factor when it comes to the result of the brazed joints since it will affect the properties of the brazed joint, such as:

- The possibility for voids to be created inside the joint when the filler material has solidified.
- The possibility for inter-metallic phases to be created inside the joint when the filler material has solidified.

- The capillary action and force which will distribute the filler material in the joint.

The way and amount the flux was applied on the joints were examined due to entrapped flux being a common problem during brazing. The main cause for entrapped flux is due to the design of the joint does not allow the flux to flow out of the joint. When the technical drawings were studied could it be seen that the flux could escape from the bottom of the stainless steel fitting pipe, however, could flux still be entrapped in the joint. Therefore was first of all the amount of flux applied examined. Between the minimal amount and the generous amount could a small difference be seen, but not a significant change for the context with voids and inclusions. The same result applies to how the flux was applied. Flux applied under the rings with a minimal amount of flux, illustrated in Figure 3.7, showed a small change in the X-ray result, but not a significant change for the context with voids and inclusions. In other words could entrapped flux is excluded as a main affecting parameter causing the unfilled quality requirement of the joints.

According to the theory is clean surfaces free from grease, dirt, and oxides are important to achieve sound brazed joints. Insufficiently cleaned surfaces will result in a decrease of the capillary forces and will affect the wetting and flow of the filler material. Therefore was different types of surface perceptions made, both mechanical and chemical. Between Batch 8 and 9 was this made, and no significant difference could be seen. In other words could surface preparations be excluded as a main affecting parameter causing the unfilled quality requirement of the joints. Something that also speaks for this is that this type of surface preparation is not performed during the manual soldering, which produces satisfied joints.

When examining the results from the measured gaps compared with the result from X-ray could it be seen that the parts included in both connections, NR3 and NR4, was in the tolerance limits set on the technical drawings. In other words, are the tolerances of the dimensions of the supplied materials for the connections not affecting the production of the joints. However, the designed gap itself could affect the production of the induction brazed joints. Regarding the results of the gaps related to the best/blocked joints compared to the average of the nine batches, could no significant conclusion be done.

5.3 Potential affecting parameters for the induction brazing process at the company

When examining the potential defects in brazed joints that were described in Section 2.4.1 and the defects related to the induction brazed connection of NR3 and NR4 are the major defects voids, inclusions, and skew pipes. As described in Section 2.4.1 are the reason for these voids and inclusions due to incomplete flow of the filler material in the joint gap. Some of the potential causes for the incomplete flow are:

- Inadequate filler material.

- Entrapped gas.
- Inappropriate joint gap.
- Movement of parts of the assembly when filler material is in the molten state. (Can also be different thermal expansions of the including material in the assembly.)
- Improper surface cleaning of the base materials.
- Entrapped flux.

To start with the inadequate filler material cause, can it be seen in the experimental part that flux-integrated filler material did not work for this application. However, the solid filler material produced decent visual joint and acceptable X-ray results but included voids and other inclusions. Worth mentioning is that this type of solid filler material is used as rods at the manual brazing with a satisfying result. The preforms rings of the solid filler material used at the induction brazing process are also recommended by the filler material supplier for this type of application. It is recommended for capillary brazing of ferrous metals like stainless steel and copper as base metals, which is used in this investigated application for this project. In other words could this cause be depreciated. The entrapped flux cause for voids could also be depreciated through the experimental part with was discussed in Section 5.2, where different ways and the amount of the flux was applied was tested. This results in no significant difference related to the voids inside the joints. The improper surface cleaning of the base materials cause could also be depreciated. This is due to the experimental test between Batch 8 and 9, where careful surface preparations of the surface showed no significant difference related to the voids inside the joints.

The induction brazing process is performed in the air with added nitrogen inside the pipes. The added nitrogen gas inside the pipes could cause entrapped gas and this is something this project has not treated or experimented with. This can be a potential source of error for this project. However, when examining how the gas is provided inside the pipe in combination with examining the technical drawings of the connections can it be said that the gas is not "blow" to the joint area. Instead the purpose of the nitrogen gas is to protect the inside of the pipes during the heating of the brazing process from oxide formation. The purpose is not to reduce the oxide formation in the joint area. At the joint the flux is used to reduce oxide formation. Something that also proves that the entrapped gas is not a cause for the voids and the inclusions is that the same solution how the gas is provided inside the pipes is used at the manual flame brazing for the same application. At the manual brazing can no evidence of entrapped gas be seen. In other words could this cause depreciated.

Inappropriate joint gap cause for voids and inclusions was discussed in the section above. At the current design, the gaps for the connection are designed for manual brazing with gaps between 0.190 mm to 0.335 mm (gaps for manual brazing can be up to 0.500 mm). However, when it comes to induction brazing is the recommended gap up to 0.130 mm to achieve good joints. By means of this can the joint gap be seen as a potential affecting parameter for the induction brazing process. When it comes to moving parts during the filler material is in the molten state as a cause for voids, has it been seen that the lack of centering has made pipes are "jumping" during the heat cycle. Skew pipes have also been an indication of movements of parts during the process. The copper pipe and the stainless steel fitting have similar thermal expansion values so this will not significantly affect movements of the parts. By means of this can the movements of the part during the brazing process be seen as a potential affecting parameters for the induction brazing process due to the lack of centering of the part.

When studying influential parameters related to induction brazing are some of them:

- Coil design and the positioning of the workpiece related to the induction coil.
- Accurate and stable process of the induction machine.
- The materials of the base and filler materials need to be consistent.
- Fixture and centering of the part of the brazing assembly.

Through the investigation of the efficiency of the coil could it be seen that the coils were well adapted for this application. In other words could this cause of voids and inclusions to be depreciated. The fixture and centering of the parts have already been discussed and can be a potential influential parameter. The behavior and accuracy of the induction machine are hard to tell. Some variations between connections in the same batch with the same induction machine program have been seen during the experimental test, but these variations are negligible when it comes to voids and inclusions. In other words could this cause of voids and inclusions most likely to be depreciated and the machine can be seen as stable.

When it comes to the consistency of the used materials could it be seen that the dimensions are within the set tolerance limits from the technical drawings. However, the consistency and composition of the materials from the suppliers are hard to draw a conclusion about. Consistency of the composition of the material is important due to reliance must be placed on the supplier that the composition material is within the tolerance limits. With other words could this cause for voids and inclusions most likely be depreciated.

5.4 Answers on research questions

Research question 1: Which are the main affecting parameters causing the unfilled quality requirement of the joint?

Answer: Too big gaps for connections NR3 and NR4 are probably the main affecting parameter for the cause for the unfilled quality requirement of the joints. The current design and gaps are suited for manual brazing but not for automatic brazing, such as induction brazing. Also, lack of centering could be a potential affecting parameter.

Research question 2: Which different solutions could possibly help meeting the quality requirements?

Answer: Smaller gaps for connection NR3 and NR4. This can be achieved by a larger outer diameter of the copper pipe to adjust the gap of the connections to the recommended joint gaps for silver brazing and induction brazing. The next step could be to design the connections to be centered during the brazing operation, for example with chamfers in the bottom of the stainless steel fitting pipe. This will automatically center the copper pipe and minimise the risk of an uneven gap around the joint. With other words changing the design of the joints and suggestions is recommended in Section 5.5 below.

5.5 Recommendations and further studies

At the current design is the joint gap between 0.190 - 0.255 mm according to calculations from the technical drawings for connection NR3. The copper pipe thickness for NR3 is 1.0 mm. For NR4 at the current design are the joint gap between 0.270 - 0.335 mm. The copper pipe thickness for NR4 is 0.8 mm. A cautious conclusion is that the remaining quality problems with voids and inclusions depend on the too large joint gaps for connections NR3 and NR4, as Figure 4.1 illustrated. In the figure, calculated values of the maximum and minimum values of the gap for each connection/joint are compared with recommended values for silver brazing from *Karlebo Handbook* (Björklund et al., 2015).

A recommendation is therefore to increase the outer diameter of the copper pipe and maintain the same dimension for the fitting pipe of stainless steel. This is due to a change in the dimensions that will affect the mass that needs to be heated during the induction brazing. However, due to the 22 times higher thermal conductivity for the copper pipe compared with the fitting of stainless steel, this will lead to the copper will spread the heat 22 times faster than the steel. A few percent extra material and mass for the pipe will probably not affect the induction brazing process and the associated induction programs. Stainless steel has also a higher specific heat capacity than copper, which means that less energy is required for the copper pipe to reach brazing temperature. This also means that the stainless steel is the influential part that will affect the brazing temperature of the whole joint. Two suggestions on solutions can be recommended, both with increased outer diameter for the copper pipe. The first solution is to keep the same thickness of the pipe (in other words, increase both the outer and inner diameter of the pipe), called Solution number 1. Solution number 2 is instead to keep the same inner diameter of the pipe (in other words, to increase the thickness of the pipe and increase only the outer diameter).

For Solution number 1, can the outer diameter for NR3 could be increased by about 1.5 % from 15.88 to 16.12 mm. To keep the same thickness of the pipe the inner diameter for NR3 must be increased by about 1.7 % from 13.88 to 14.12 mm. This will lead to a decrease in the maximum gap of 51 % from 0.255 to 0.125 mm. It will also lead to a decrease in the minimum gap with 63 % from 0.190 to 0.070 mm.

When it comes to NR4 for Solution number 1, the outer diameter can be increased by about 4.4 % from 9.52 to 9.94 mm. To keep the same thickness of the pipe the inner diameter for NR4 must be increased by about 5.3 % from 7.92 to 8.34 mm. This will lead to a decrease of the maximum gap with 63 % from 0.335 to 0.125 mm. It will also lead to a decrease in the minimum gap with 78 % from 0.270 to 0.060 mm.

For Solution number 2, the outer diameter for NR3 can be increased with about 1.5 % from 15.88 to 16.12 mm. To keep the same inner diameters of the pipe, the nominal thickness of the pipe for NR3 must be increased by about 12 % from 1.0 to 1.12 mm. This will lead to a decrease of the maximum gap with 51 % from 0.255 to 0.125 mm. This will also lead to a decrease of the minimum gap with 63 % from 0.190 to 0.070 mm. When it comes to NR4 for Solution number 2, the outer diameter for NR4 can be increased with about 4.4 % from 9.52 to 9.94 mm. To keep the same inner diameters of the pipe, the nominal thickness of the pipe for NR4 must be increased by about 26 % from 0.80 to 1.01 mm. This will lead to a decrease in the maximum gap with 63 % from 0.335 to 0.125 mm. This will also lead to a decrease in the minimum gap with 78 % from 0.270 to 0.060 mm.

Both the solutions will decrease the joint gaps for both connections as described above and the design of the joint and the connections will be more adapted to induction brazing (automatic process) with silver brazed brazing filler material, which can be illustrated in Figure 2.10. Here it can be seen that different gaps are recommended to a different type of methods, especially between automatic methods like induction brazing, compared to manual brazing which is more adapted for larger gaps. This is probably the reason why voids and inclusions arise more or less for each type of different settings and parameters tested during this master's thesis project for the induction brazing at the company.

Recommended further studies for the specific product at the company is to use copper pipes with larger outer diameter for the connection NR3 and NR4, proposed Solution number 1 or 2 presented above. Either purchase other pipe dimensions or simply extend the lower part of the pipe with a special tool and "kraga" in Swedish the pipes to the right dimensions for further experiments. Recommended is to use Program 1_4, the solid filler material with the amount of two rings, and to use a little amount of flux under the rings, described in Chapter 3. These settings have shown a good visual appearance on the joints and the most acceptable results from X-ray according to the experimental part of this master's thesis. Surface preparations are always beneficial for the brazing process, to the extent possible for the test production at the company. An important note is that new dimensions of the pre-forms (the rings) are required for the new dimensions of the copper pipes for NR3 and NR4. A solution for lack of centering of the pipe inside the stainless steel fitting pipe is as mentioned can be fixtures or to design the parts with chamfers to center the parts right with help of the assembly construction, for example, to design a chamfers at the bottom of the stainless steel fitting pipe. This will help to ensure an even joint gap around the joint and reduce the risk of skew pipes.

6

Conclusion

As conclusions for this master's thesis project could it be drawn that the main affecting parameter for the quality problems with voids and inclusions most likely is that the gaps are too big for the connections NR3 and NR4. The current design of the joints is adjusted to manual brazing. The manual flame brazing performs joints with high-quality joints. However when it comes to induction brazing smaller gaps are required to achieve sound joints, something that many theoretical sources recommend, and the experimental part of this project has indicated. Proposed solutions are based on that copper pipes with bigger outer diameters are used for connection NR3 and NR4 to reduce the gap in the range between 0.050 mm to 0.130 mm instead of gap in the range between 0.190 to 0.350 mm. Reduced gaps will contribute according to the theory, to an increase of the capillary flow of the filler material during the brazing operation. In combination with smaller gaps and better flow, will probably the risk for voids and other inclusion be reduced. Another influencing parameter is the centering of the copper pipe inside the stainless steel fitting during the brazing operation to reduce the risk for moments during the process and to secure an even gap width around the joint. A solution for this could be a change in the design with chamfers in the bottom of the stainless steel fitting pipe. This in turn will create a more stable induction brazing process for this specific application and hopefully enable the current induction brazing station to be put into full use in production at the company. However further test has to be done to validate if smaller gaps reduce the presence of voids and inclusions.

To conclude the master's thesis, it is important to highlight that the gap of the connections is the main parameter causing the quality problems. The conclusion is based on the experimental and theoretical studies made during the master's thesis. However, with that concluded, it is not excluded that other factors may affect the problems with voids and inclusions of the joints since it may be a combination of several factors.

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A

Appendix A

Experimental test plan

Batch 1					
Ex nr:	**Program:**	**Filler material:**	**Amount:**	**Flux:**	**Surface preparation:**
1	1	Solid	2 rings	Yes, applied above rings (generous amount)	Mechanical nr 1
2	1	Solid	2 rings	Yes, applied above rings (generous amount)	Mechanical nr 1
3	1	Solid	2 rings	Yes, applied above rings (generous amount)	Mechanical nr 1
4	1	Solid	2 rings	Yes, applied above rings (generous amount)	None
5	1	Solid	2 rings	Yes, applied above rings (generous amount)	None
6	1_1	Solid	2 rings	Yes, applied above rings (generous amount)	Mechanical nr 1
7	1_1	Solid	2 rings	Yes, applied above rings (generous amount)	Mechanical nr 1
8	1_1	Solid	2 rings	Yes, applied above rings (generous amount)	Mechanical nr 1
9	1_2	Solid	2 rings	Yes, applied above rings (generous amount)	None
10	1_2	Solid	2 rings	Yes, applied above rings (generous amount)	None
Batch 2					
Ex nr:	**Program:**	**Filler material:**	**Amount:**	**Flux:**	**Surface preparation:**
11	1_2	Solid	2 rings	Yes, applied above rings (generous amount)	Mechanical nr 2
12	1_2	Solid	2 rings	Yes, applied above rings (generous amount)	Mechanical nr 2
13	1_2	Solid	2 rings	Yes, applied above rings (generous amount)	Mechanical nr 2
14	1_2	Solid	2 rings	Yes, applied above rings (generous amount)	Mechanical nr 2
15	1_2	Solid	2 rings	Yes, applied above rings (generous amount)	Mechanical nr 2
16	1_2	Solid	2 rings	Yes, applied above rings (generous amount)	Mechanical nr 2
17	1_2	Solid	2 rings	Yes, applied above rings (generous amount)	Mechanical nr 2
18	1_2	Solid	2 rings	Yes, applied above rings (generous amount)	Mechanical nr 2
19	1_2	Solid	2 rings	Yes, applied above rings (generous amount)	Mechanical nr 2

20	1_2	Solid	2 rings	Yes, applied above rings (generous amount)	Mechanical nr 2
Batch 3					
Ex nr:	**Program:**	**Filler material:**	**Amount:**	**Flux:**	**Surface preparation:**
21	1_3	Solid	2 rings	Yes, applied above rings (little amount)	None
22	1_3	Solid	2 rings	Yes, applied above rings (little amount)	None
23	1_3	Solid	2 rings	Yes, applied above rings (little amount)	None
24	1_3	Solid	2 rings	Yes, applied above rings (little amount)	None
25	1_3	Solid	2 rings	Yes, applied above rings (little amount)	None
26	1_3	Solid	2 rings	Yes, applied above rings (little amount)	None
27	1_3	Solid	2 rings	Yes, applied above rings (little amount)	None
28	1_3	Solid	2 rings	Yes, applied above rings (little amount)	None
29	1_3	Solid	2 rings	Yes, applied above rings (little amount)	None
30	1_3	Solid	2 rings	Yes, applied above rings (little amount)	None
Batch 4					
Ex nr:	**Program:**	**Filler material:**	**Amount:**	**Flux:**	**Surface preparation:**
31	1_3	Solid	3 rings	Yes, applied above rings (little amount)	None
32	1_3	Solid	2 rings	Yes, applied under rings (little amount)	None
33	1_3	Solid	2 rings	Yes, applied under rings (little amount)	None
34	1_3	Solid	2 rings	Yes, applied under rings (little amount)	None
35	1_3	Solid	2 rings	Yes, applied under rings (little amount)	None
36	5	Flux-integrated	1 ring	None	None
37	5_1	Flux-integrated	1 ring	None	None
38	5_2	Flux-integrated	1 ring	None	None
39	1_3	Flux-integrated	1 ring	None	None
40	Manual brazing	Flux-integrated	1 ring	None	None
Batch 5					
Ex nr:	**Program:**	**Filler material:**	**Amount:**	**Flux:**	**Surface preparation:**
41	1_4	Solid	2 rings	Yes, applied under rings (little amount)	None
42	1_4	Solid	2 rings	Yes, applied under rings (little amount)	None
43	1_4	Solid	2 rings	Yes, applied under rings (little amount)	None

44	1_4	Solid	2 rings	Yes, applied under rings (little amount)	None
45	1_4	Solid	2 rings	Yes, applied under rings (little amount)	None
46	3, 3_1, 3_2, 3_3	Flux-integrated	1 ring	None	None
47	3_4	Flux-integrated	1 ring	None	None
48	3_5	Flux-integrated	1 ring	None	None
49	3_6	Flux-integrated	1 ring	None	None
50	3_7	Flux-integrated	1 ring	None	None
Batch 6					
Ex nr:	**Program:**	**Filler material:**	**Amount:**	**Flux:**	**Surface preparation:**
51	3_8 + extra on NR4	Flux-integrated	1 ring	None	None
52	3_9	Flux-integrated	1 ring	None	None
53	3_10	Flux-integrated	1 ring	None	None
54	3_11	Flux-integrated	1 ring	None	None
55	3_12	Flux-integrated	1 ring	None	None
56	3_12	Flux-integrated	1 ring	None	None
57	3_12	Flux-integrated	1 ring	None	None
58	3_12	Flux-integrated	1 ring	None	None
59	3_12	Flux-integrated	1 ring	None	None
60	3_12	Flux-integrated	1 ring	None	None
Batch 7					
Ex nr:	**Program:**	**Filler material:**	**Amount:**	**Flux:**	**Surface preparation:**
61	3_13	Flux-integrated	1 ring	None	None
62	3_14 + extra on NR4	Flux-integrated	1 ring	None	None
63	3_15	Flux-integrated	1 ring	None	None
64	3_16	Flux-integrated	1 ring	None	None
65	3_17	Flux-integrated	1 ring	None	None
66	3_18	Flux-integrated	1 ring	None	None
67	3_16	Flux-integrated	1 ring	None	None
68	3_16	Flux-integrated	1 ring	None	None
69	3_16	Flux-integrated	1 ring	None	None
70	3_16	Flux-integrated	1 ring	None	None
Batch 8					
Ex nr:	**Program:**	**Filler material:**	**Amount:**	**Flux:**	**Surface preparation:**
71	1_4	Solid	2 rings	Yes, applied under rings (little amount)	Mechanical nr 2 and Chemical
72	1_4	Solid	2 rings	Yes, applied under rings (little amount)	Mechanical nr 2 and Chemical
73	1_4	Solid	2 rings	Yes, applied under rings (little amount)	Mechanical nr 2 and Chemical
74	1_4	Solid	2 rings	Yes, applied under rings (little amount)	Mechanical nr 2 and Chemical
75	1_4	Solid	2 rings	Yes, applied under rings (little amount)	Mechanical nr 2 and Chemical
76	1_4	Solid	2 rings	Yes, applied under rings (little amount)	Mechanical nr 2 and Chemical
77	1_4	Solid	2 rings	Yes, applied under rings (little amount)	Mechanical nr 2 and Chemical
78	1_4	Solid	2 rings	Yes, applied under rings (little amount)	Mechanical nr 2 and Chemical

79	1_4	Solid	2 rings	Yes, applied under rings (little amount)	Mechanical nr 2 and Chemical
80	1_4	Solid	2 rings	Yes, applied under rings (little amount)	Mechanical nr 2 and Chemical
Batch 9					
Ex nr:	**Program:**	**Filler material:**	**Amount:**	**Flux:**	**Surface preparation:**
81	1_4	Solid	2 rings	Yes, applied under rings (little amount)	None
82	1_4	Solid	2 rings	Yes, applied under rings (little amount)	None
83	1_4	Solid	2 rings	Yes, applied under rings (little amount)	None
84	1_4	Solid	2 rings	Yes, applied under rings (little amount)	None
85	1_4	Solid	2 rings	Yes, applied under rings (little amount)	None
86	1_4	Solid	2 rings	Yes, applied under rings (little amount)	None
87	1_4	Solid	2 rings	Yes, applied under rings (little amount)	None
88	1_4	Solid	2 rings	Yes, applied under rings (little amount)	None
89	1_4	Solid	2 rings	Yes, applied under rings (little amount)	None
90	1_4	Solid	2 rings	Yes, applied under rings (little amount)	None

B

Appendix B

Induction machine programs in figure-form

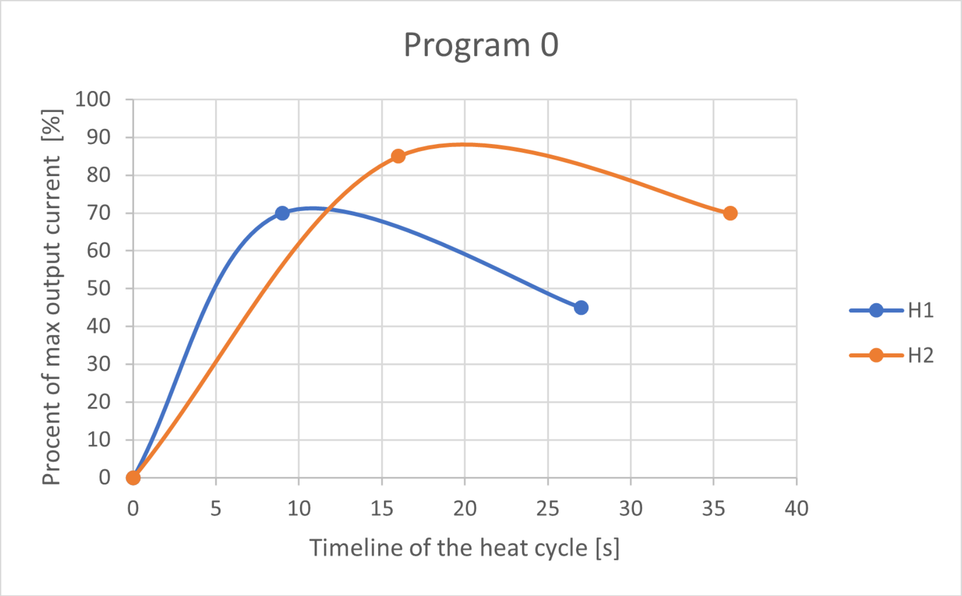

Figure B1: Illustration of induction machine Program 0 for coil H1 respectively H2.

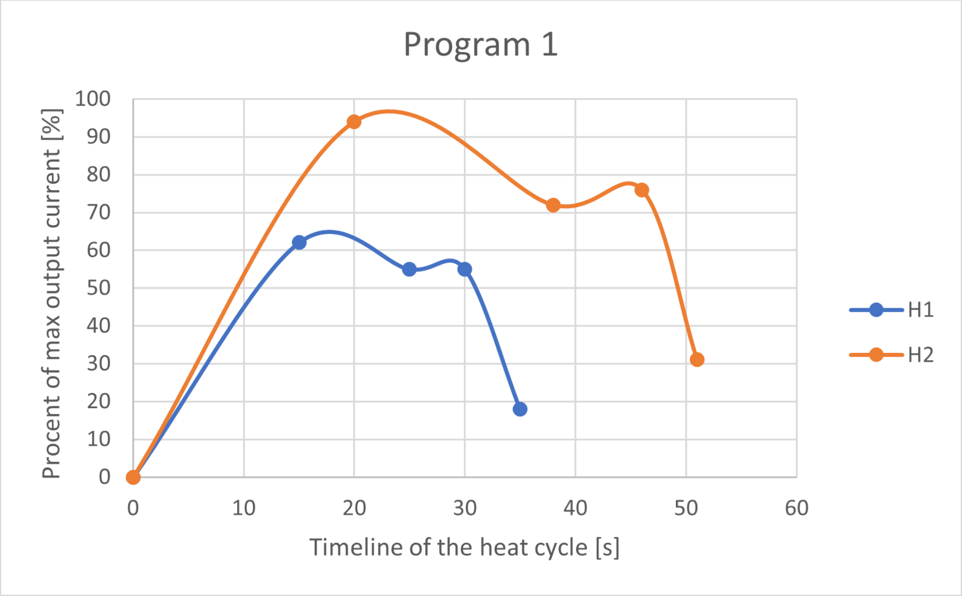

Figure B2: Illustration of induction machine Program 1 for coil H1 respectively H2.

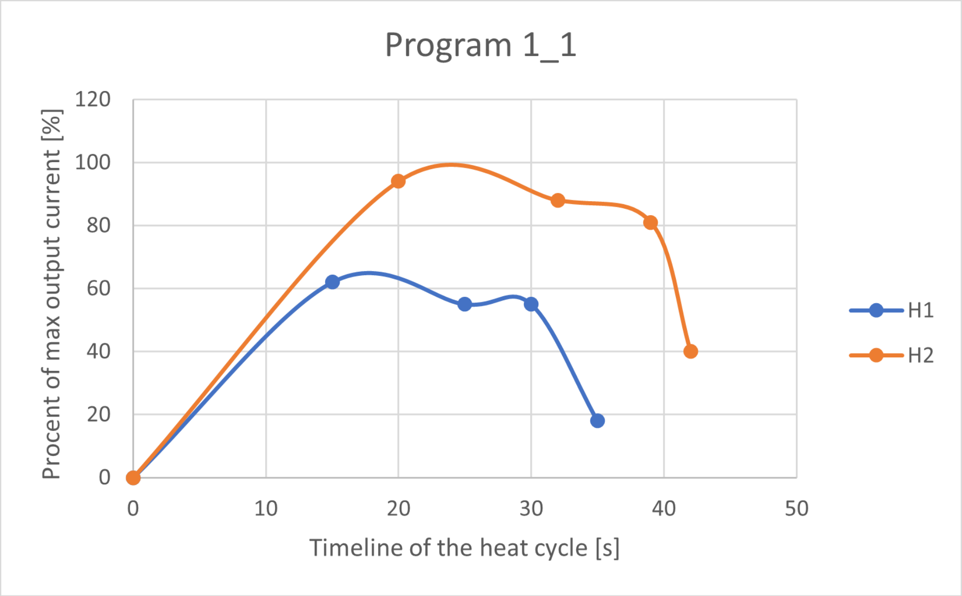

Figure B3: Illustration of induction machine Program 1_1 for coil H1 respectively H2.

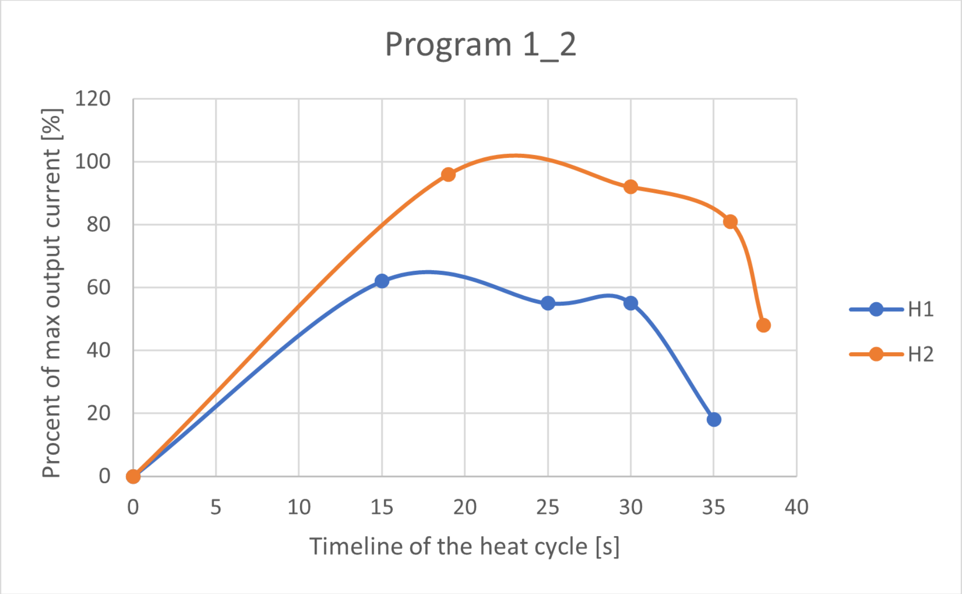

Figure B4: Illustration of induction machine Program 1_2 for coil H1 respectively H2.

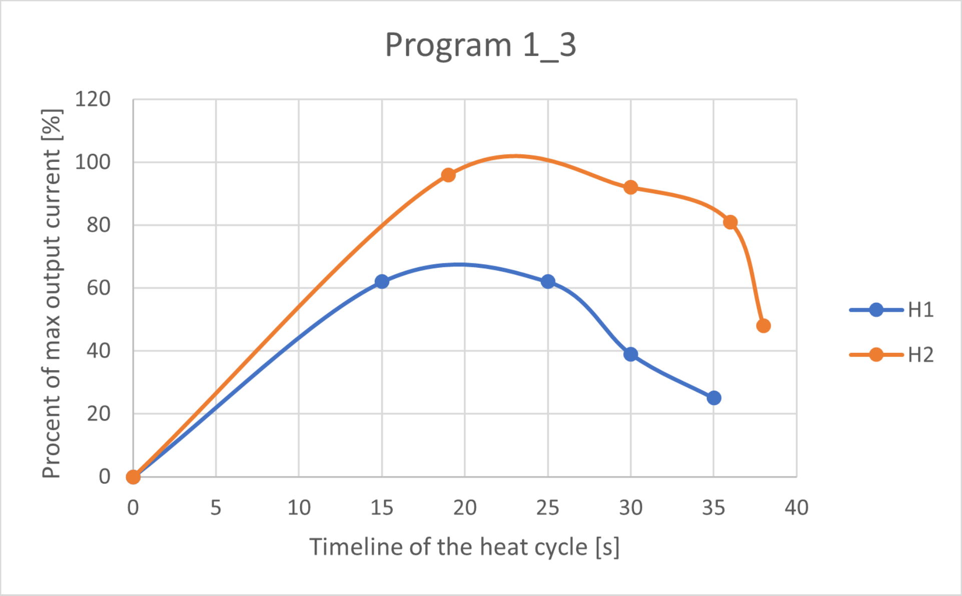

Figure B5: Illustration of induction machine Program 1_3 for coil H1 respectively H2.

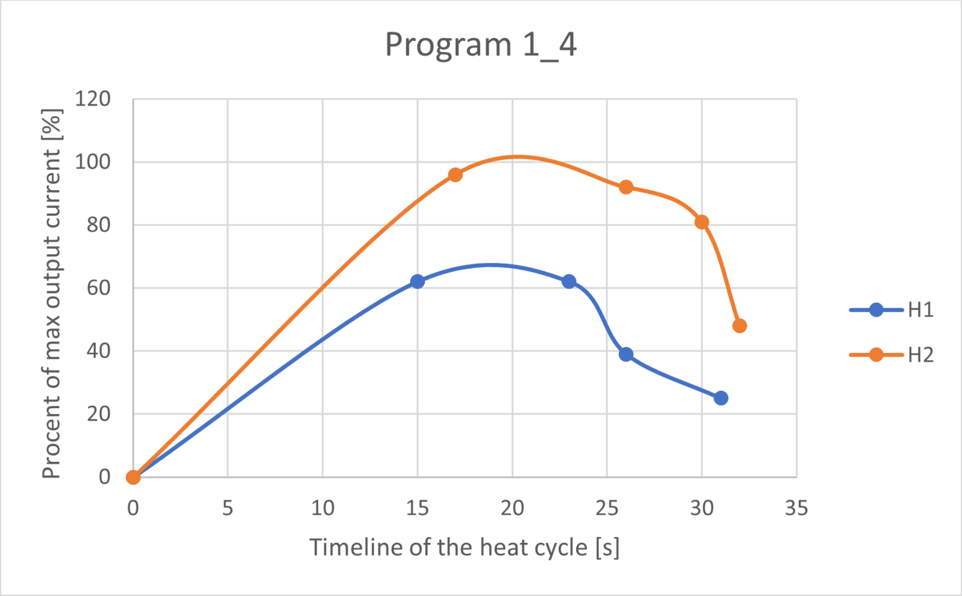

Figure B6: Illustration of induction machine Program 1_4 for coil H1 respectively H2.

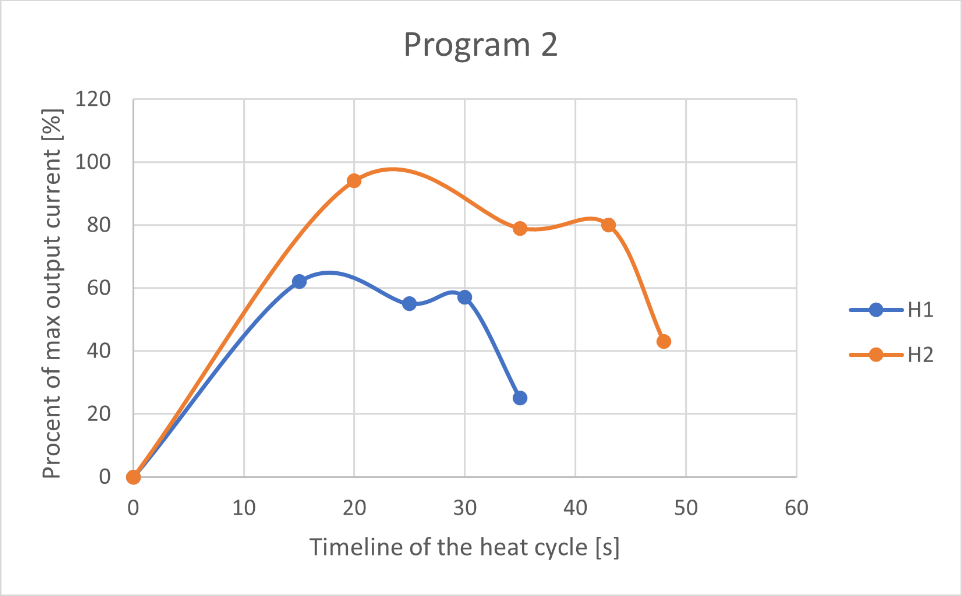

Figure B7: Illustration of induction machine Program 2 for coil H1 respectively H2.

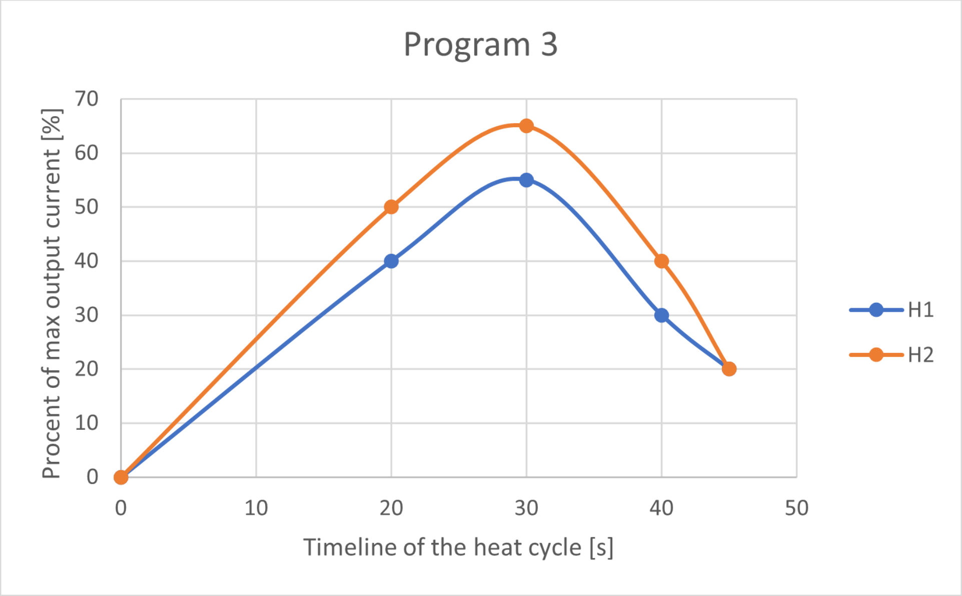

Figure B8: Illustration of induction machine Program 3 for coil H1 respectively H2.

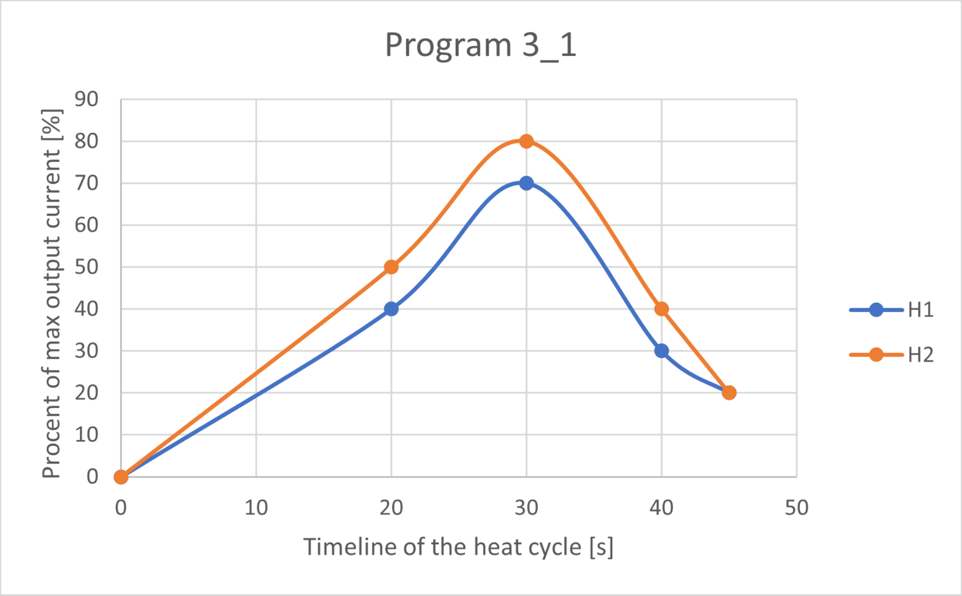

Figure B9: Illustration of induction machine Program 3_1 for coil H1 respectively H2.

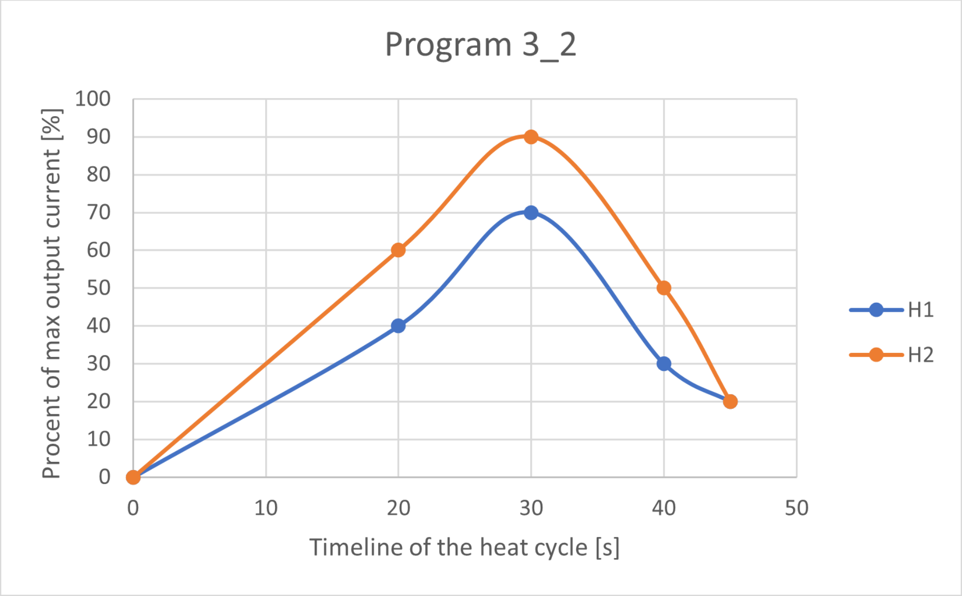

Figure B10: Illustration of induction machine Program 3_2 for coil H1 respectively H2.

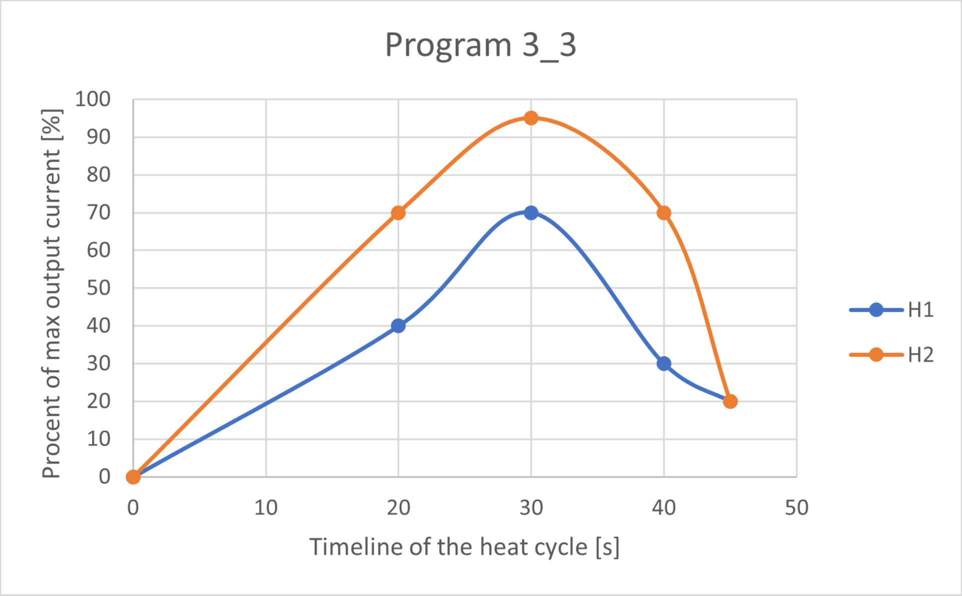

Figure B11: Illustration of induction machine Program 3_3 for coil H1 respectively H2.

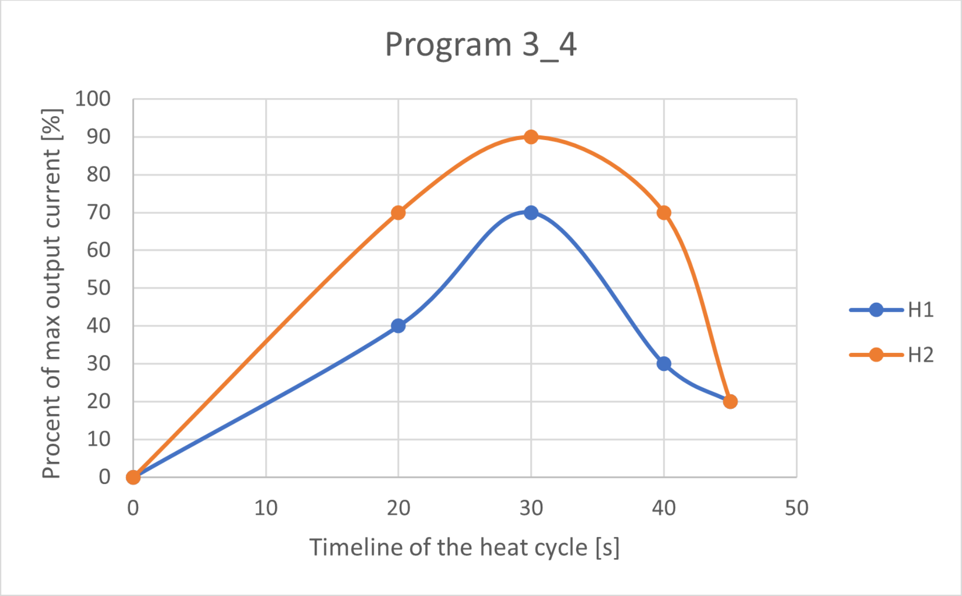

Figure B12: Illustration of induction machine Program 3_4 for coil H1 respectively H2.

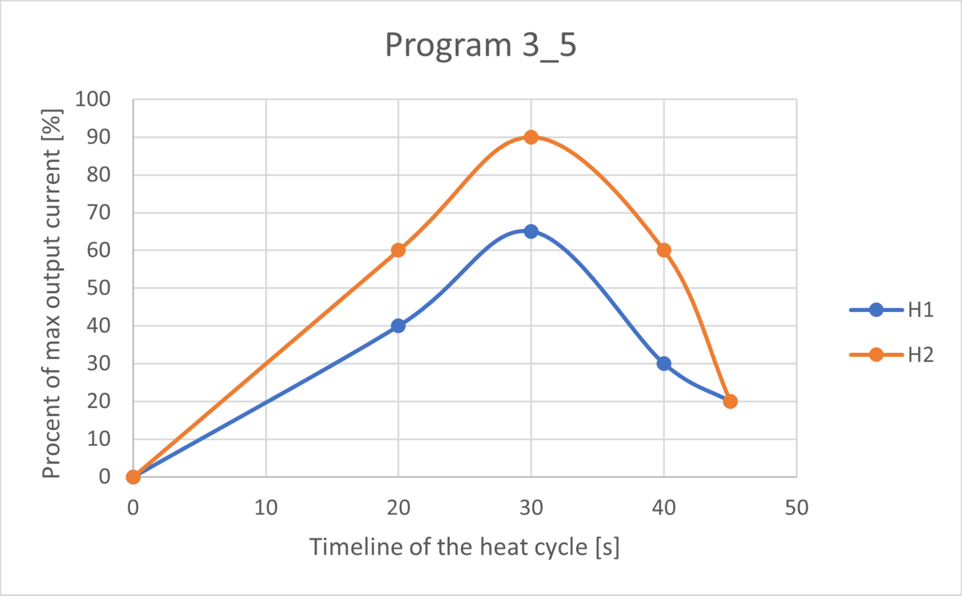

Figure B13: Illustration of induction machine Program 3_5 for coil H1 respectively H2.

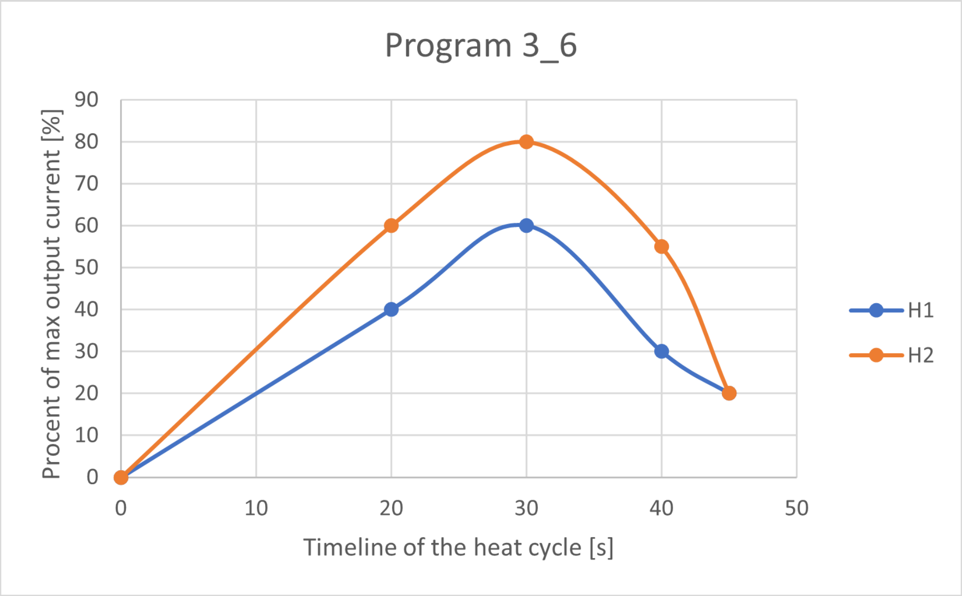

Figure B14: Illustration of induction machine Program 3_6 for coil H1 respectively H2.

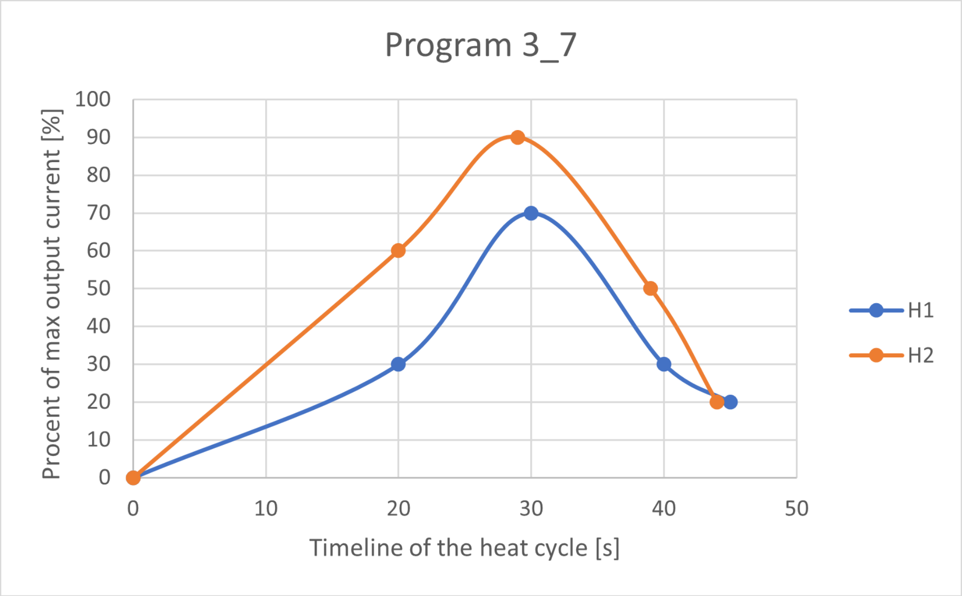

Figure B15: Illustration of induction machine Program 3_7 for coil H1 respectively H2.

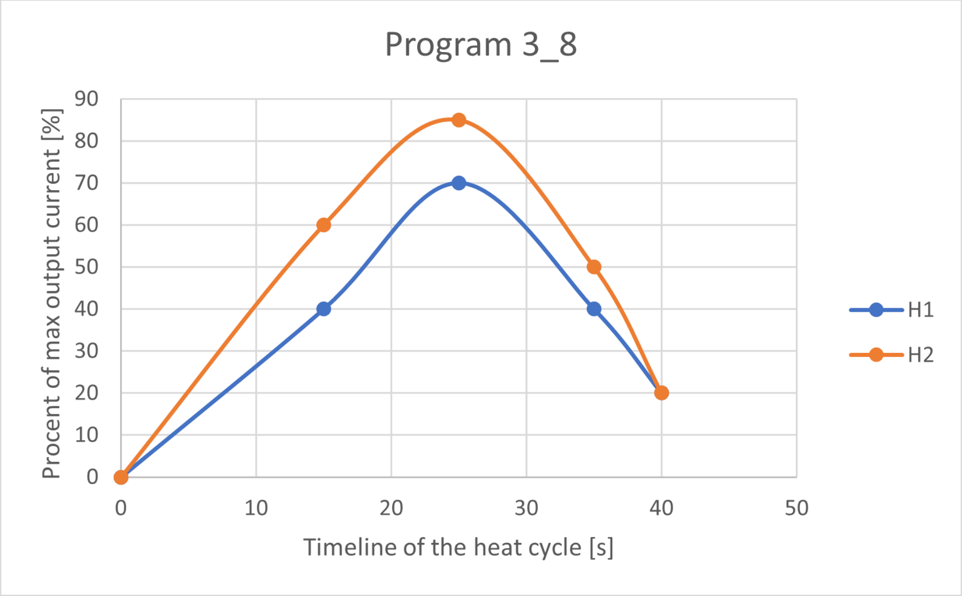

Figure B16: Illustration of induction machine Program 3_8 for coil H1 respectively H2.

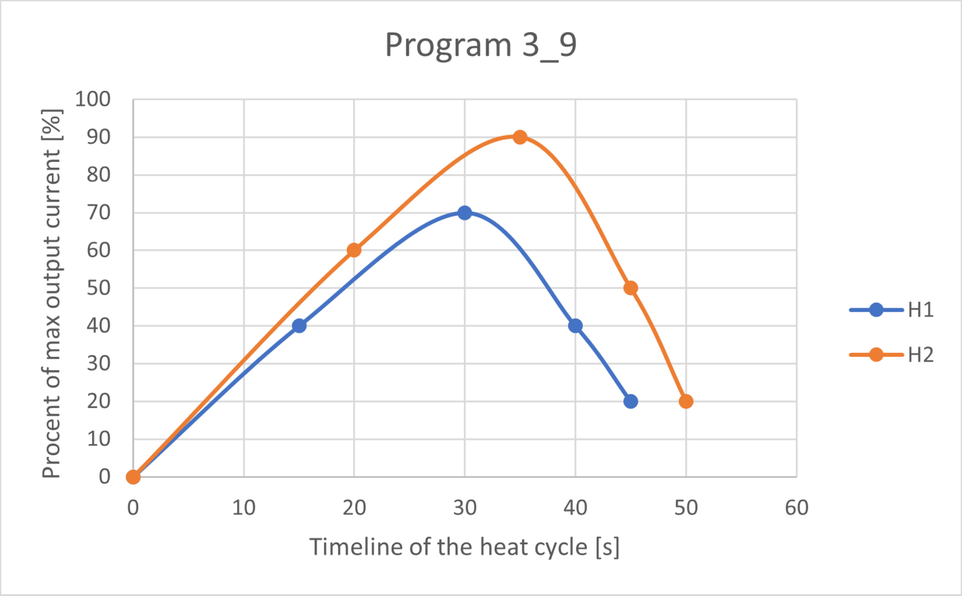

Figure B17: Illustration of induction machine Program 3_9 for coil H1 respectively H2.

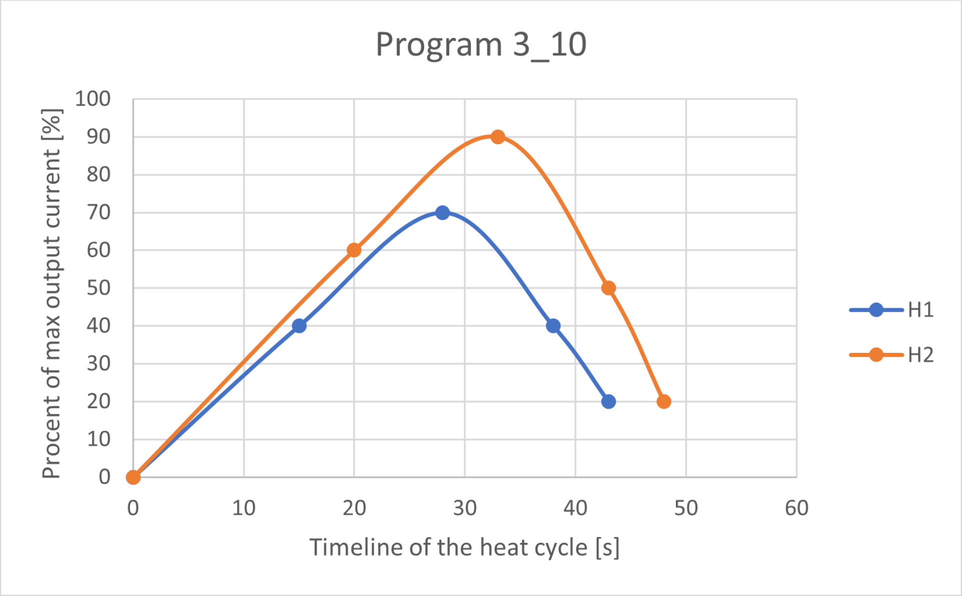

Figure B18: Illustration of induction machine Program 3_10 for coil H1 respectively H2.

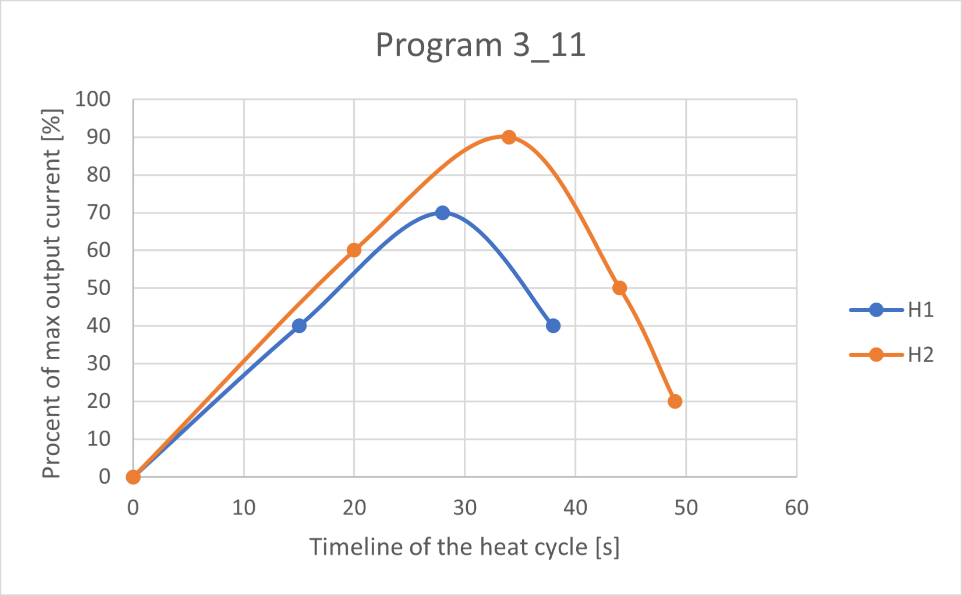

Figure B19: Illustration of induction machine Program 3_11 for coil H1 respectively H2.

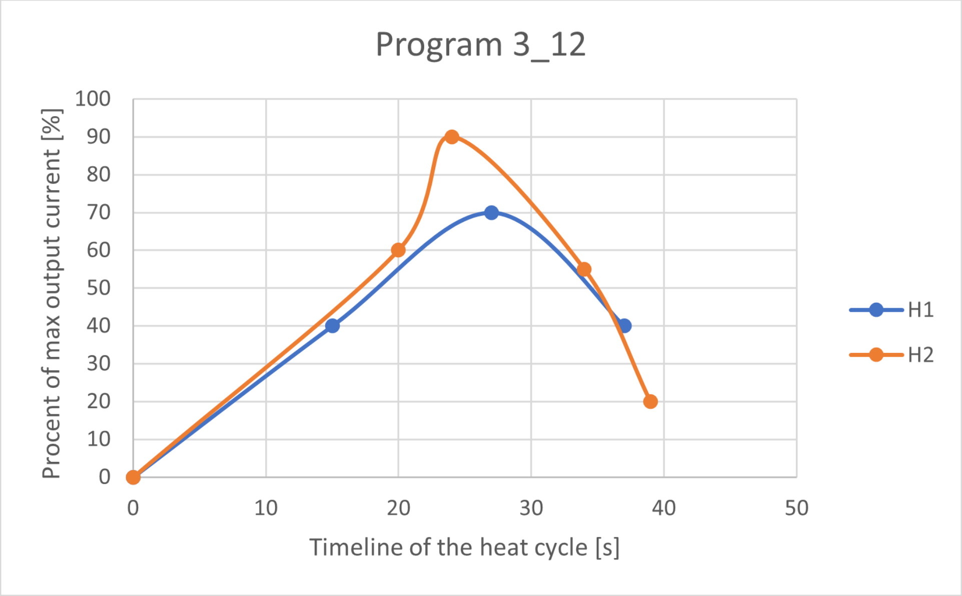

Figure B20: Illustration of induction machine Program 3_12 for coil H1 respectively H2.

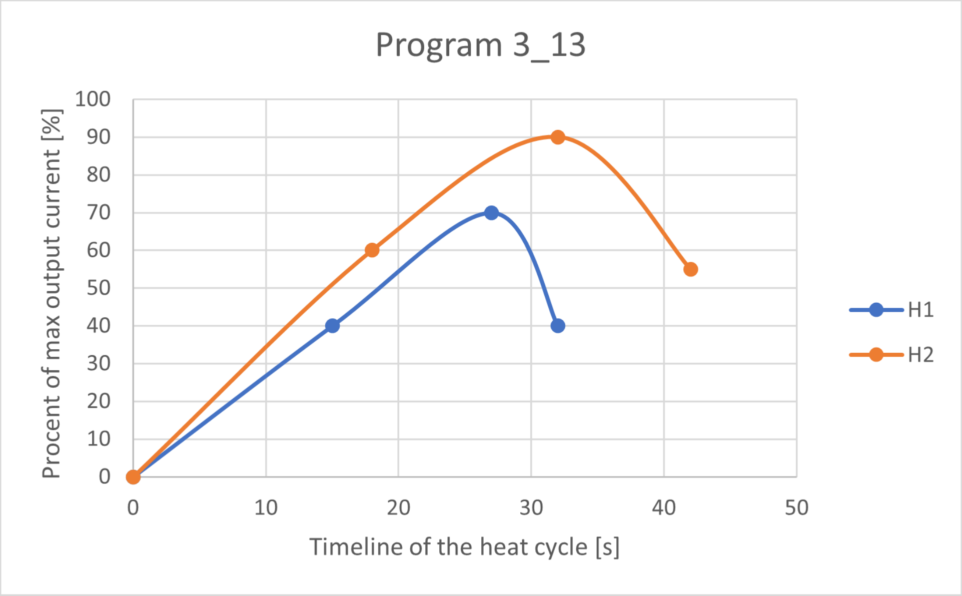

Figure B21: Illustration of induction machine Program 3_13 for coil H1 respectively H2.

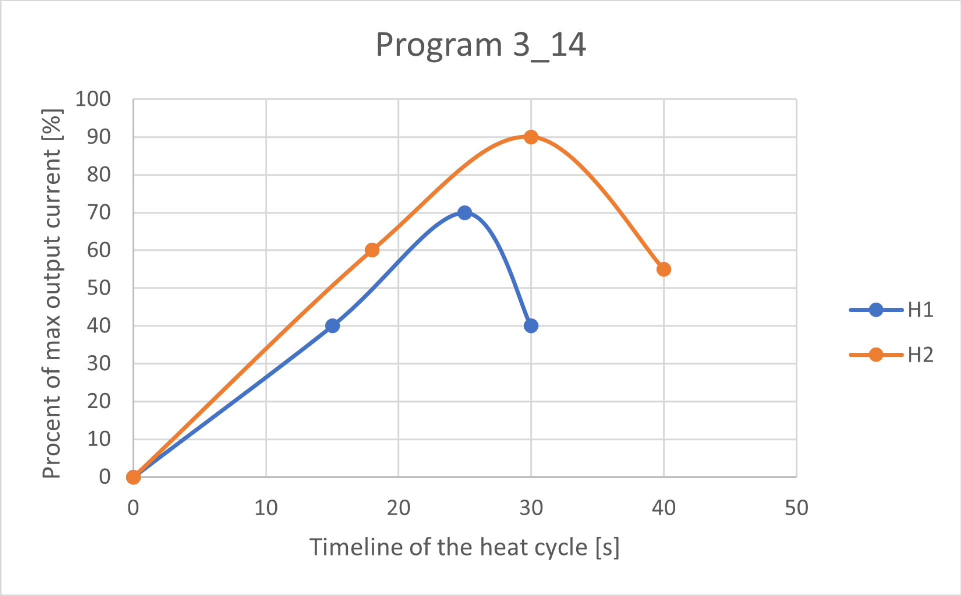

Figure B22: Illustration of induction machine Program 3_14 for coil H1 respectively H2.

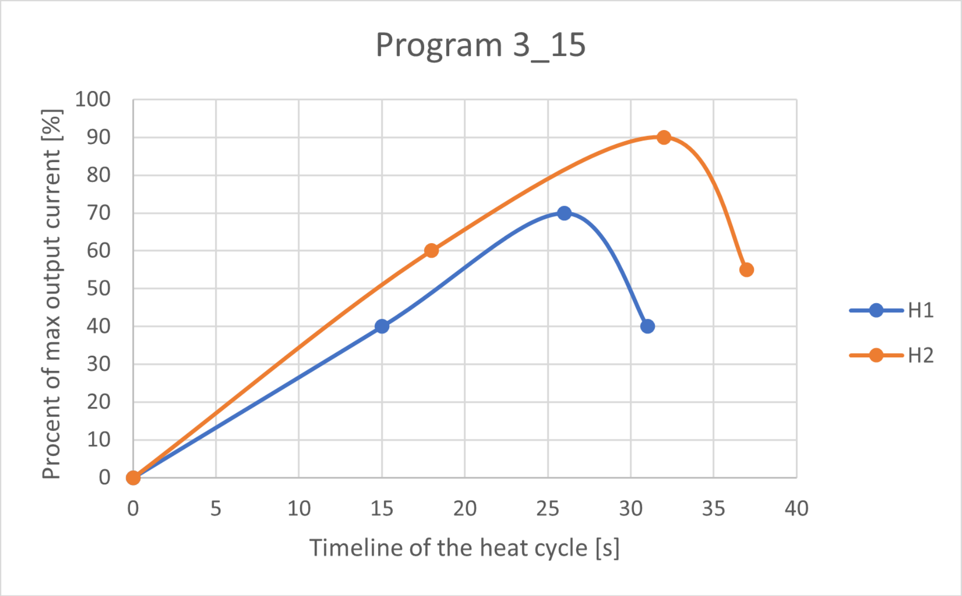

Figure B23: Illustration of induction machine Program 3_15 for coil H1 respectively H2.

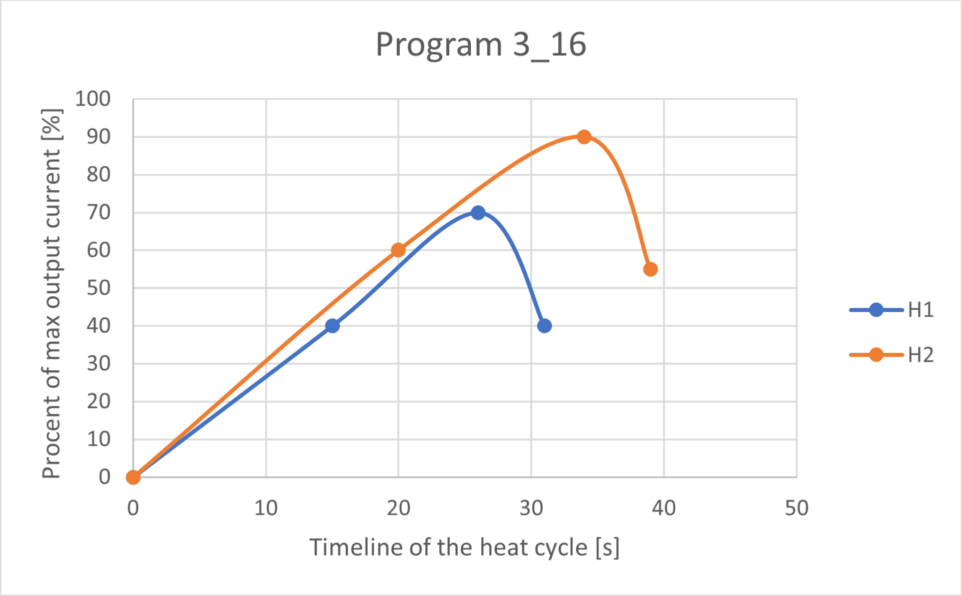

Figure B24: Illustration of induction machine Program 3_16 for coil H1 respectively H2.

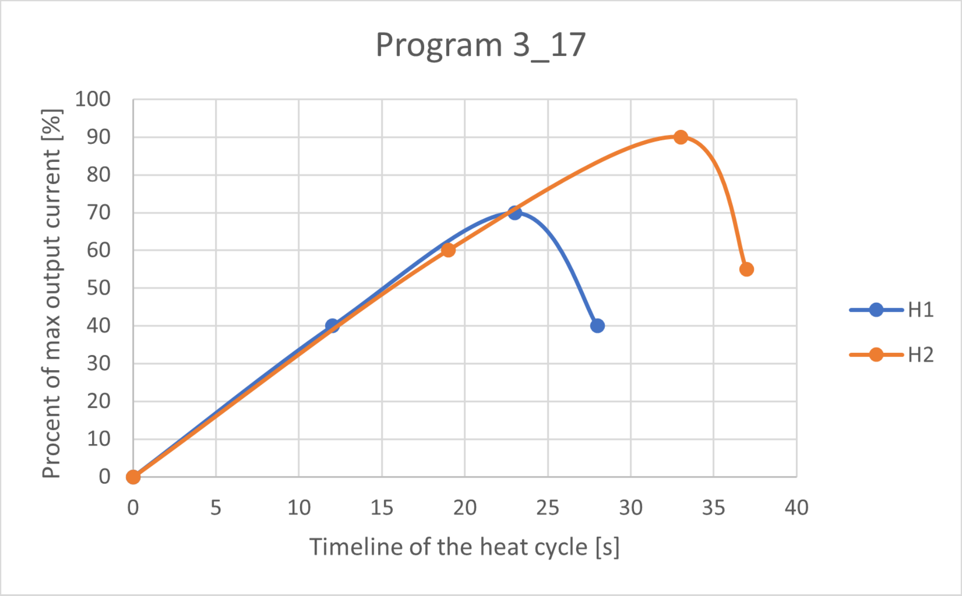

Figure B25: Illustration of induction machine Program 3_17 for coil H1 respectively H2.

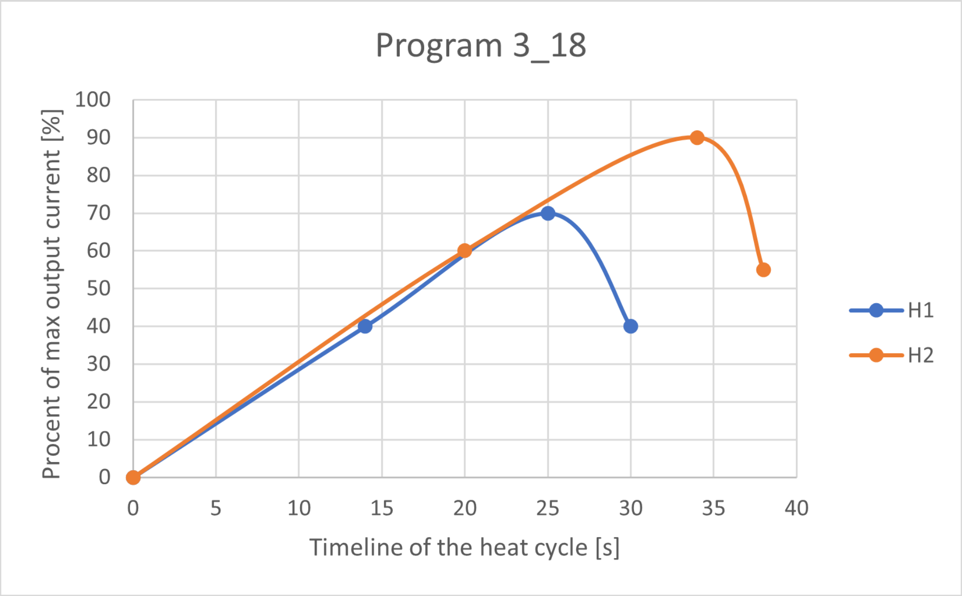

Figure B26: Illustration of induction machine Program 3_18 for coil H1 respectively H2.

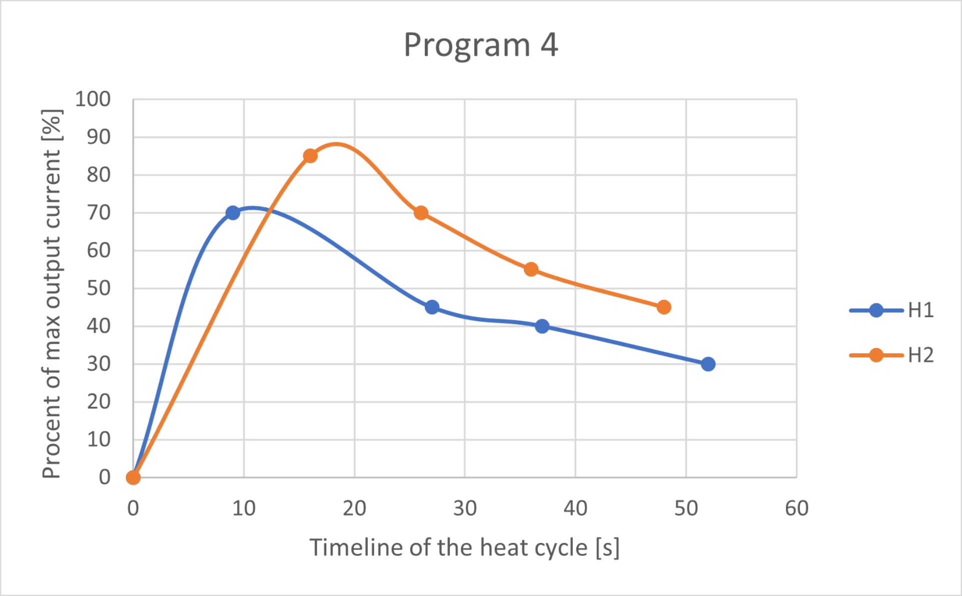

Figure B27: Illustration of induction machine Program 4 for coil H1 respectively H2.

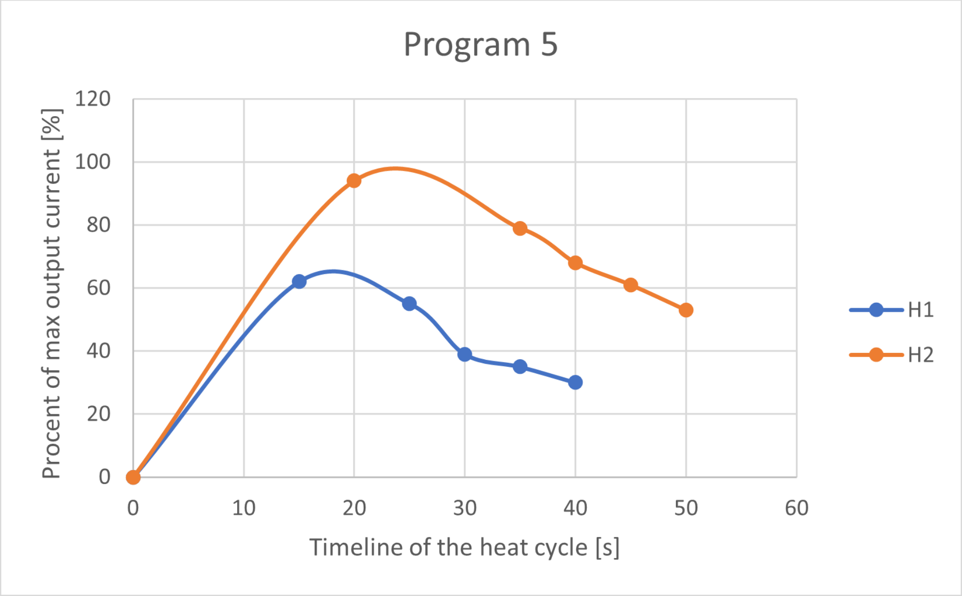

Figure B28: Illustration of induction machine Program 5 for coil H1 respectively H2.

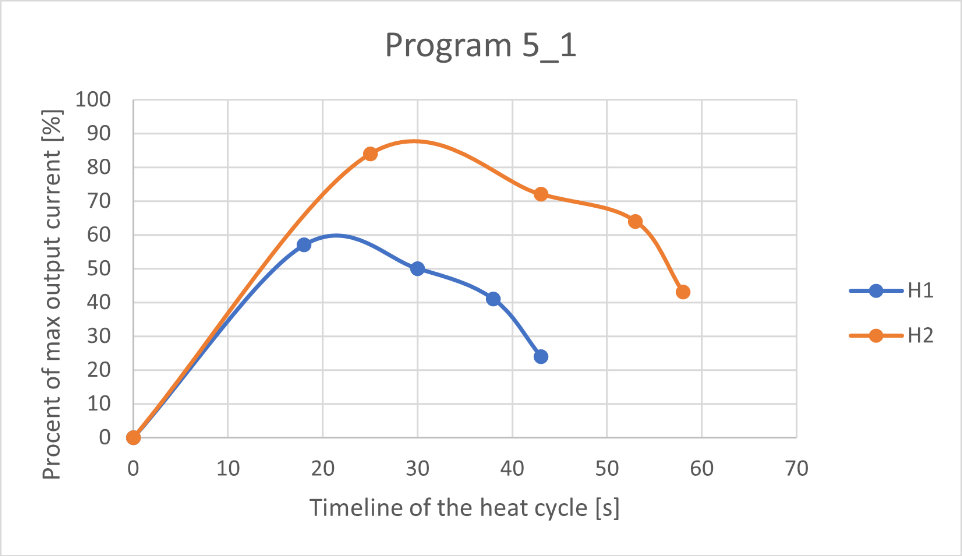

Figure B29: Illustration of induction machine Program 5_1 for coil H1 respectively H2.

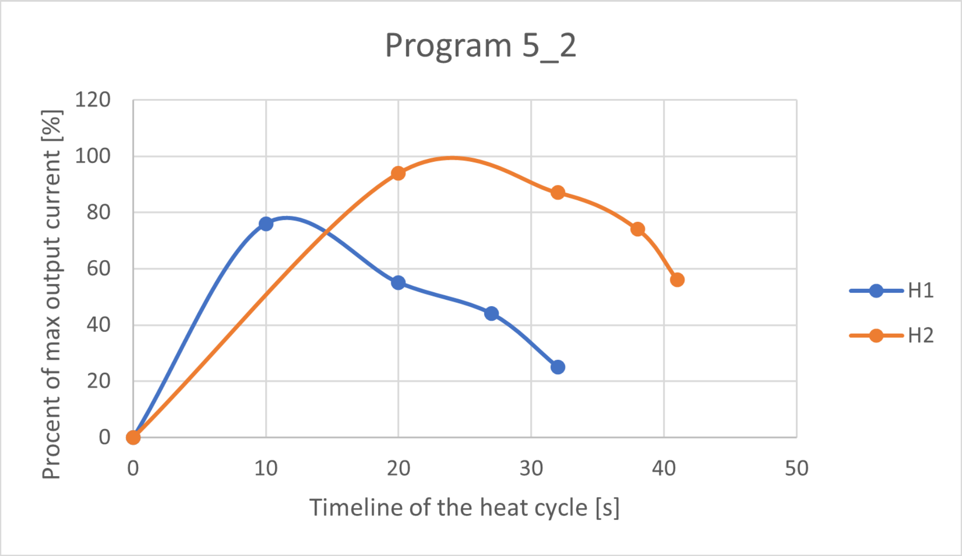

Figure B30: Illustration of induction machine Program 5_2 for coil H1 respectively H2.

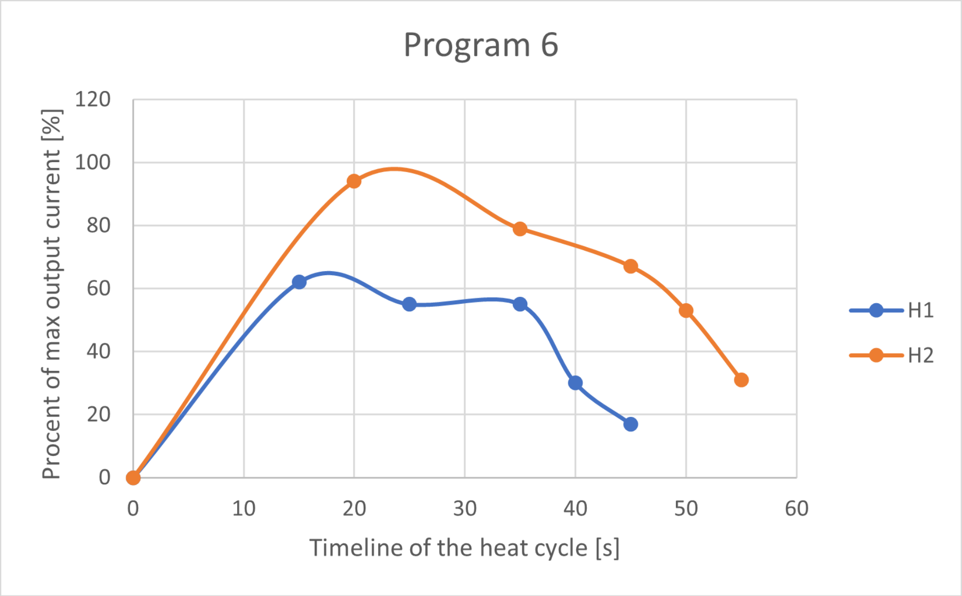

Figure B31: Illustration of induction machine Program 6 for coil H1 respectively H2.

C

Appendix C

Induction machine programs in table-form

Program 0	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	9	70
		1	Step	1s	18	45
		-	-	-	-	-
		-	-	-	-	-
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	16	85
		1	Step	1s	10	70
		-	-	-	-	-
		-	-	-	-	-
Program 1	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	15	62
		1	Step	1s	10	55
		2	Step	1s	5	55
		3	Step	1s	5	18
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	94
		1	Step	1s	18	72
		2	Step	1s	8	76
		3	Step	1s	5	31
Program 1_1	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	15	62
		1	Step	1s	10	55
		2	Step	1s	5	55
		3	Step	1s	5	18
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	94
		1	Step	1s	12	88
		2	Step	1s	7	81
		3	Step	1s	3	40

Program 1_2	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	15	62
		1	Step	1s	10	55
		2	Step	1s	5	55
		3	Step	1s	5	18
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	19	96
		1	Step	1s	11	92
		2	Step	1s	6	81
		3	Step	1s	2	48
Program 1_3	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	15	62
		1	Step	1s	10	62
		2	Step	1s	5	39
		3	Step	1s	5	25
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	19	96
		1	Step	1s	11	92
		2	Step	1s	6	81
		3	Step	1s	2	48
Program 1_4	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	15	62
		1	Step	1s	8	62
		2	Step	1s	3	39
		3	Step	1s	5	25
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	17	96
		1	Step	1s	9	92
		2	Step	1s	4	81
		3	Step	1s	2	48

Program 2	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	15	62
		1	Step	1s	10	55
		2	Step	1s	5	57
		3	Step	1s	5	25
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	94
		1	Step	1s	15	79
		2	Step	1s	8	80
		3	Step	1s	5	43
Program 3	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	20	40
		1	Step	1s	10	55
		2	Step	1s	10	30
		3	Step	1s	5	20
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	50
		1	Step	1s	10	65
		2	Step	1s	10	40
		3	Step	1s	5	20
Program 3_1	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	20	40
		1	Step	1s	10	70
		2	Step	1s	10	30
		3	Step	1s	5	20
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	50
		1	Step	1s	10	80
		2	Step	1s	10	40
		3	Step	1s	5	20

Program 3_2	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	20	40
		1	Step	1s	10	70
		2	Step	1s	10	30
		3	Step	1s	5	20
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	60
		1	Step	1s	10	90
		2	Step	1s	10	50
		3	Step	1s	5	20
Program 3_3	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	20	40
		1	Step	1s	10	70
		2	Step	1s	10	30
		3	Step	1s	5	20
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	70
		1	Step	1s	10	95
		2	Step	1s	10	70
		3	Step	1s	5	20
Program 3_4	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	20	40
		1	Step	1s	10	70
		2	Step	1s	10	30
		3	Step	1s	5	20
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	70
		1	Step	1s	10	90
		2	Step	1s	10	70
		3	Step	1s	5	20

Program 3_5	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	20	40
		1	Step	1s	10	65
		2	Step	1s	10	30
		3	Step	1s	5	20
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	60
		1	Step	1s	10	90
		2	Step	1s	10	60
		3	Step	1s	5	20
Program 3_6	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	20	40
		1	Step	1s	10	60
		2	Step	1s	10	30
		3	Step	1s	5	20
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	60
		1	Step	1s	10	80
		2	Step	1s	10	55
		3	Step	1s	5	20
Program 3_7	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	20	30
		1	Step	1s	10	70
		2	Step	1s	10	30
		3	Step	1s	5	20
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	60
		1	Step	1s	9	90
		2	Step	1s	10	50
		3	Step	1s	5	20

	Coil - H1	Segment nr:	Type:	Time unit:	Time (s):	Target setpoint (%):
Program 3_8	Connection NR3	0	Step	1s	15	40
		1	Step	1s	10	70
		2	Step	1s	10	40
		3	Step	1s	5	20
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	15	60
		1	Step	1s	10	85
		2	Step	1s	10	50
		3	Step	1s	5	20

	Coil - H1	Segment nr:	Type:	Time unit:	Time (s):	Target setpoint (%):
Program 3_9	Connection NR3	0	Step	1s	15	40
		1	Step	1s	15	70
		2	Step	1s	10	40
		3	Step	1s	5	20
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	60
		1	Step	1s	15	90
		2	Step	1s	10	50
		3	Step	1s	5	20

	Coil - H1	Segment nr:	Type:	Time unit:	Time (s):	Target setpoint (%):
Program 3_10	Connection NR3	0	Step	1s	15	40
		1	Step	1s	13	70
		2	Step	1s	10	40
		3	Step	1s	5	20
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	60
		1	Step	1s	13	90
		2	Step	1s	10	50
		3	Step	1s	5	20

Program 3_11	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	15	40
		1	Step	1s	13	70
		2	Step	1s	10	40
		3				
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	60
		1	Step	1s	14	90
		2	Step	1s	10	50
		3	Step	1s	5	20
Program 3_12	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	15	40
		1	Step	1s	12	70
		2	Step	1s	10	40
		3				
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	60
		1	Step	1s	14	90
		2	Step	1s	10	55
		3	Step	1s	5	20
Program 3_13	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	15	40
		1	Step	1s	12	70
		2	Step	1s	5	40
		3				
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	18	60
		1	Step	1s	14	90
		2	Step	1s	10	55
		3				

Program 3_14	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	15	40
		1	Step	1s	10	70
		2	Step	1s	5	40
		3				
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	18	60
		1	Step	1s	12	90
		2	Step	1s	10	55
		3				
Program 3_15	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	15	40
		1	Step	1s	11	70
		2	Step	1s	5	40
		3	Step			
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	18	60
		1	Step	1s	14	90
		2	Step	1s	5	55
		3				
Program 3_16	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	15	40
		1	Step	1s	11	70
		2	Step	1s	5	40
		3	Step			
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	60
		1	Step	1s	14	90
		2	Step	1s	5	55
		3				

Program 3_17	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	12	40
		1	Step	1s	11	70
		2	Step	1s	5	40
		3	Step			
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	19	60
		1	Step	1s	14	90
		2	Step	1s	4	55
		3				
Program 3_18	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	14	40
		1	Step	1s	11	70
		2	Step	1s	5	40
		3	Step			
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	60
		1	Step	1s	14	90
		2	Step	1s	4	55
		3				
Program 4	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	9	70
		1	Step	1s	18	45
		2	Step	1s	10	40
		3	Step	1s	15	30
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	16	85
		1	Step	1s	10	70
		2	Step	1s	10	55
		3	Step	1s	12	45

Program 5	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	15	62
		1	Step	1s	10	55
		2	Step	1s	5	39
		3	Step	1s	5	35
		4	Step	1s	5	30
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	94
		1	Step	1s	15	79
		2	Step	1s	5	68
		3	Step	1s	5	61
		4	Step	1s	5	53
Program 5_1	**Coil - H1**	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR3	0	Step	1s	18	57
		1	Step	1s	12	50
		2	Step	1s	8	41
		3	Step	1s	5	24
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	25	84
		1	Step	1s	18	72
		2	Step	1s	10	64
		3	Step	1s	5	43

	Coil - H1	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
Program 5_2	Connection NR3	0	Step	1s	10	76
		1	Step	1s	10	55
		2	Step	1s	7	44
		3	Step	1s	5	25
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	94
		1	Step	1s	12	87
		2	Step	1s	6	74
		3	Step	1s	3	56
	Coil - H1	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
Program 6	Connection NR3	0	Step	1s	15	62
		1	Step	1s	10	55
		2	Step	1s	5	55
		3	Step	1s	5	30
		4	Step	1s	5	17
	Coil - H2	**Segment nr:**	**Type:**	**Time unit:**	**Time (s):**	**Target setpoint (%):**
	Connection NR4	0	Step	1s	20	94
		1	Step	1s	15	79
		2	Step	1s	10	67
		3	Step	1s	5	53
		4	Step	1s	5	31

D

Appendix D

Complete results for Batch 1 - 9

Batch 1					
Ex nr:	**Program:**	**Filler material:**	**NR3 visual inspection:**	**NR4 visual inspection:**	**Result X-ray:**
1	1	Solid	Good	Too hot for to long time	No X-ray
2	1	Solid	Good	Too hot for to long time	No X-ray
3	1	Solid	Good	Too hot for to long time	No X-ray
4	1	Solid	Good	Too hot for to long time	No X-ray
5	1	Solid	Good	Too hot for to long time	No X-ray
6	1_1	Solid	Good	On the limit but good	Good, but some voids and on the limit
7	1_1	Solid	Good	On the limit but good	Good, but some voids and on the limit
8	1_1	Solid	Good	On the limit but good	Good, but some voids and on the limit
9	1_2	Solid	Good, but a bit over the edge	Good	Good, but some voids and on the limit
10	1_2	Solid	Good, but a bit over the edge	Good	Good, but some voids and on the limit

Batch 2					
Ex nr:	**Program:**	**Filler material:**	**NR3 visual inspection:**	**NR4 visual inspection:**	**Result X-ray:**
11	1_2	Solid	Good	Good	Good, still some voids
12	1_2	Solid	Little far down	Good	Good, still some voids
13	1_2	Solid	Little far down	Good	Good, still some voids
14	1_2	Solid	Good	Good	Good, still some voids
15	1_2	Solid	Good	Good	Good, still some voids
16	1_2	Solid	Good	Good	Good, still some voids
17	1_2	Solid	Good	Good	Good, still some voids
18	1_2	Solid	Little far down	Good	Good, still some voids
19	1_2	Solid	Little far down	Good	Good, still some voids

20	1_2	Solid	Good	Good	Good, still some voids
Batch 3					
Ex nr:	**Program:**	**Filler material:**	**NR3 visual inspection:**	**NR4 visual inspection:**	**Result X-ray:**
21	1_3	Solid	Good, on the limit far down	Good	Good, but some voids, larger but in fewer amount
22	1_3	Solid	Good, on the limit far down	Bad, too little flux maybe. To far down. Visual not ok.	Not good
23	1_3	Solid	Good, on the limit far down	Good	Good, but some voids, larger but in fewer amount
24	1_3	Solid	Good, on the limit far down	Good	Good, but some voids, larger but in fewer amount
25	1_3	Solid	Good, on the limit far down	Good	Good, but some voids, larger but in fewer amount
26	1_3	Solid	Good, on the limit far down	Bad, too little flux maybe. To far down	Good, but some voids, larger but in fewer amount
27	1_3	Solid	Good, on the limit far down	Bad, too little flux maybe. To far down	Good, but some voids, larger but in fewer amount
28	1_3	Solid	Good, on the limit far down	Good, on the limit far down	Good, but some voids, larger but in fewer amount
29	1_3	Solid	Good, on the limit far down	Bad, too little flux maybe. To far down	Good, but some voids, larger but in fewer amount
30	1_3	Solid	Good, on the limit far down	Bad, too little flux maybe. To far down	Good, but some voids, larger but in fewer amount
Batch 4					
Ex nr:	**Program:**	**Filler material:**	**NR3 visual inspection:**	**NR4 visual inspection:**	**Result X-ray:**
31	1_3	Solid	Bad	Bad	Good, but some voids
32	1_3	Solid	Good. Maybe little hot or far down, but good	Good. Maybe little hot or far down, but good	Good, but some voids
33	1_3	Solid	Good. Maybe little hot or far down, but good	Good. Maybe little hot or far down, but good	Good, but some voids
34	1_3	Solid	Good. Maybe little hot or far down, but good	Good. Maybe little hot or far down, but good	Good, but some voids

35	1_3	Solid	Good. Maybe little hot or far down, but good	Good. Maybe little hot or far down, but good	Good, but some voids
36	5	Flux-integrated	Not so good, unsure if good. Too hot.	Not so good, unsure if good. Too hot.	Voids and not visually ok
37	5_1	Flux-integrated	Not so good, unsure if good. Too hot.	Not so good, unsure if good. Too hot.	Blocked
38	5_2	Flux-integrated	Not so good, unsure if good. Too hot.	Not so good, unsure if good. Too hot.	Blocked
39	1_3	Flux-integrated	Not so good, unsure if good. Too hot.	Not so good, unsure if good. Too hot.	Blocked
40	Manual brazing	Flux-integrated	Noot good. Manual fix to see diffemce when ring was heated by flame.	Noot good. Manual fix to see diffemce when ring was heated by flame.	Blocked
Batch 5					
Ex nr:	**Program:**	**Filler material:**	**NR3 visual inspection:**	**NR4 visual inspection:**	**Result X-ray:**
41	1_4	Solid	Good	Good	Good, but some voids
42	1_4	Solid	Good	Good	Good, but something bad with NR4. Blocked.
43	1_4	Solid	Good	Good	Good, but some voids
44	1_4	Solid	Good	Good	Good, but some voids
45	1_4	Solid	Good	Good	Good, but some voids
46	3, 3_1, 3_2, 3_3	Flux-integrated	Bad	Bad	No X-ray
47	3_4	Flux-integrated	Bad	Bad	Blocked
48	3_5	Flux-integrated	Bad	Bad	Blocked
49	3_6	Flux-integrated	Bad	Bad	No X-ray
50	3_7	Flux-integrated	Bad	Bad	No X-ray
Batch 6					
Ex nr:	**Program:**	**Filler material:**	**NR3 visual inspection:**	**NR4 visual inspection:**	**Result X-ray:**
51	3_8 + extra on NR4	Flux-integrated	Not ok	Not ok	No X-Ray
52	3_9	Flux-integrated	Not ok	Not ok	No X-Ray
53	3_10	Flux-integrated	Not ok	One the limit	No X-Ray
54	3_11	Flux-integrated	Not ok	One the limit	No X-Ray
55	3_12	Flux-integrated	On the limit	One the limit	Bad
56	3_12	Flux-integrated	On the limit	One the limit	Blocked
57	3_12	Flux-integrated	On the limit	One the limit	Blocked
58	3_12	Flux-integrated	On the limit	One the limit, some pockets	Blocked
59	3_12	Flux-integrated	On the limit	One the limit	Blocked
60	3_12	Flux-integrated	On the limit	One the limit	Blocked
Batch 7					

Ex nr:	**Program:**	**Filler material:**	**NR3 visual inspection:**	**NR4 visual inspection:**	**Result X-ray:**
61	3_13	Flux-integrated	On the limit	Not good	Blocked
62	3_14 + extra on NR4	Flux-integrated	On the limit	Really not good	No X-Ray
63	3_15	Flux-integrated	On the limit	Not good	Blocked
64	3_16	Flux-integrated	Good	Good	Bad but ok
65	3_17	Flux-integrated	Not good	Good, but some pockets	Blocked
66	3_18	Flux-integrated	Good	Good	Blocked
67	3_16	Flux-integrated	Good	On the limit	Blocked
68	3_16	Flux-integrated	Good	On the limit	Blocked
69	3_16	Flux-integrated	Good	On the limit	Blocked
70	3_16	Flux-integrated	Good	Not good	Blocked

Batch 8

Ex nr:	**Program:**	**Filler material:**	**NR3 visual inspection:**	**NR4 visual inspection:**	**Result X-ray:**
71	1_4	Solid	Good	Good	Good, but some voids
72	1_4	Solid	Good	Good	Good, on NR4 pipe skew and only filler on one side, blocked
73	1_4	Solid	Good	Good	Good, but some voids
74	1_4	Solid	Good	Good	Good, but some voids
75	1_4	Solid	Good	Good	Good, but some voids
76	1_4	Solid	Good	Good	Good, but some voids
77	1_4	Solid	Good	Good	Good, but some voids
78	1_4	Solid	Good	Good	Good, but some voids
79	1_4	Solid	Good	Good	Good, but some voids
80	1_4	Solid	Good	Good	Good, but some voids

Batch 9

Ex nr:	**Program:**	**Filler material:**	**NR3 visual inspection:**	**NR4 visual inspection:**	**Result X-ray:**
81	1_4	Solid	Good	Good	Good, but some voids
82	1_4	Solid	Good	Good	Good, but some voids
83	1_4	Solid	Good	Good	Good, but some voids
84	1_4	Solid	Good	Good	Good, but some voids

85	1_4	Solid	Good	Good	Good, but some voids, but bad NR4, blocked
86	1_4	Solid	Good	Good	Good, but some voids
87	1_4	Solid	Good	Good	Good, but some voids, but bad NR4, blocked
88	1_4	Solid	Good	Good	Good, but some voids
89	1_4	Solid	Good	Good	Good, on NR4 pipe skew and only filler on one side, blocked
90	1_4	Solid	Good	Good	Good, but some voids

E

Appendix E

Complete gap measurements for Batch 1 - 9

<table>
<tr><th colspan="5">Batch 1</th></tr>
<tr><th>Ex nr:</th><th>Program:</th><th>Filler material:</th><th>Gap NR3 [mm]:</th><th>Gap NR4 [mm]:</th></tr>
<tr><td>**1**</td><td>1</td><td>Solid</td><td>0,235</td><td>0,285</td></tr>
<tr><td>**2**</td><td>1</td><td>Solid</td><td>0,235</td><td>0,305</td></tr>
<tr><td>**3**</td><td>1</td><td>Solid</td><td>0,235</td><td>0,275</td></tr>
<tr><td>**4**</td><td>1</td><td>Solid</td><td>0,23</td><td>0,295</td></tr>
<tr><td>**5**</td><td>1</td><td>Solid</td><td>0,23</td><td>0,29</td></tr>
<tr><td>**6**</td><td>1_1</td><td>Solid</td><td>0,235</td><td>0,29</td></tr>
<tr><td>**7**</td><td>1_1</td><td>Solid</td><td>0,22</td><td>0,305</td></tr>
<tr><td>**8**</td><td>1_1</td><td>Solid</td><td>0,25</td><td>0,29</td></tr>
<tr><td>**9**</td><td>1_2</td><td>Solid</td><td>0,24</td><td>0,28</td></tr>
<tr><td>**10**</td><td>1_2</td><td>Solid</td><td>0,23</td><td>0,3</td></tr>
<tr><th colspan="5">Batch 2</th></tr>
<tr><th>Ex nr:</th><th>Program:</th><th>Filler material:</th><th>Gap NR3 [mm]:</th><th>Gap NR4 [mm]:</th></tr>
<tr><td>**11**</td><td>1_2</td><td>Solid</td><td>0,205</td><td>0,3</td></tr>
<tr><td>**12**</td><td>1_2</td><td>Solid</td><td>0,22</td><td>0,305</td></tr>
<tr><td>**13**</td><td>1_2</td><td>Solid</td><td>0,22</td><td>0,3</td></tr>
<tr><td>**14**</td><td>1_2</td><td>Solid</td><td>0,225</td><td>0,29</td></tr>
<tr><td>**15**</td><td>1_2</td><td>Solid</td><td>0,22</td><td>0,3</td></tr>
<tr><td>**16**</td><td>1_2</td><td>Solid</td><td>0,23</td><td>0,31</td></tr>
<tr><td>**17**</td><td>1_2</td><td>Solid</td><td>0,22</td><td>0,305</td></tr>
<tr><td>**18**</td><td>1_2</td><td>Solid</td><td>0,225</td><td>0,3</td></tr>
<tr><td>**19**</td><td>1_2</td><td>Solid</td><td>0,23</td><td>0,305</td></tr>
<tr><td>**20**</td><td>1_2</td><td>Solid</td><td>0,245</td><td>0,29</td></tr>
<tr><th colspan="5">Batch 3</th></tr>
<tr><th>Ex nr:</th><th>Program:</th><th>Filler material:</th><th>Gap NR3 [mm]:</th><th>Gap NR4 [mm]:</th></tr>
<tr><td>**21**</td><td>1_3</td><td>Solid</td><td>0,225</td><td>0,305</td></tr>
<tr><td>**22**</td><td>1_3</td><td>Solid</td><td>0,225</td><td>0,305</td></tr>
<tr><td>**23**</td><td>1_3</td><td>Solid</td><td>0,235</td><td>0,3</td></tr>
<tr><td>**24**</td><td>1_3</td><td>Solid</td><td>0,235</td><td>0,295</td></tr>
<tr><td>**25**</td><td>1_3</td><td>Solid</td><td>0,225</td><td>0,31</td></tr>
<tr><td>**26**</td><td>1_3</td><td>Solid</td><td>0,235</td><td>0,295</td></tr>
<tr><td>**27**</td><td>1_3</td><td>Solid</td><td>0,215</td><td>0,295</td></tr>
<tr><td>**28**</td><td>1_3</td><td>Solid</td><td>0,23</td><td>0,305</td></tr>
<tr><td>**29**</td><td>1_3</td><td>Solid</td><td>0,23</td><td>0,3</td></tr>
<tr><td>**30**</td><td>1_3</td><td>Solid</td><td>0,225</td><td>0,3</td></tr>
<tr><th colspan="5">Batch 4</th></tr>
<tr><th>Ex nr:</th><th>Program:</th><th>Filler material:</th><th>Gap NR3 [mm]:</th><th>Gap NR4 [mm]:</th></tr>
<tr><td>**31**</td><td>1_3</td><td>Solid</td><td>0,235</td><td>0,305</td></tr>
<tr><td>**32**</td><td>1_3</td><td>Solid</td><td>0,235</td><td>0,28</td></tr>
<tr><td>**33**</td><td>1_3</td><td>Solid</td><td>0,23</td><td>0,295</td></tr>
<tr><td>**34**</td><td>1_3</td><td>Solid</td><td>0,21</td><td>0,305</td></tr>
<tr><td>**35**</td><td>1_3</td><td>Solid</td><td>0,22</td><td>0,32</td></tr>
<tr><td>**36**</td><td>5</td><td>Flux-integrated</td><td>0,245</td><td>0,305</td></tr>
<tr><td>**37**</td><td>5_1</td><td>Flux-integrated</td><td>0,235</td><td>0,32</td></tr>
<tr><td>**38**</td><td>5_2</td><td>Flux-integrated</td><td>0,21</td><td>0,295</td></tr>
<tr><td>**39**</td><td>1_3</td><td>Flux-integrated</td><td>0,235</td><td>0,3</td></tr>
<tr><td>**40**</td><td>Manual brazing</td><td>Flux-integrated</td><td>0,2</td><td>0,305</td></tr>
<tr><th colspan="5">Batch 5</th></tr>
<tr><th>Ex nr:</th><th>Program:</th><th>Filler material:</th><th>Gap NR3 [mm]:</th><th>Gap NR4 [mm]:</th></tr>
</table>

41	1_4	Solid	0,23	0,31
42	1_4	Solid	0,225	0,305
43	1_4	Solid	0,22	0,3
44	1_4	Solid	0,225	0,32
45	1_4	Solid	0,22	0,315
46	3, 3_1, 3_2, 3_3	Flux-integrated	0,23	0,315
47	3_4	Flux-integrated	0,22	0,305
48	3_5	Flux-integrated	0,235	0,315
49	3_6	Flux-integrated	0,21	0,305
50	3_7	Flux-integrated	0,23	0,31
Batch 6				
Ex nr:	**Program:**	**Filler material:**	**Gap NR3 [mm]:**	**Gap NR4 [mm]:**
51	3_8 + extra on NR4	Flux-integrated	0,215	0,285
52	3_9	Flux-integrated	0,225	0,28
53	3_10	Flux-integrated	0,23	0,3
54	3_11	Flux-integrated	0,24	0,31
55	3_12	Flux-integrated	0,215	0,305
56	3_12	Flux-integrated	0,235	0,305
57	3_12	Flux-integrated	0,225	0,31
58	3_12	Flux-integrated	0,225	0,3
59	3_12	Flux-integrated	0,22	0,305
60	3_12	Flux-integrated	0,2	0,295
Batch 7				
Ex nr:	**Program:**	**Filler material:**	**Gap NR3 [mm]:**	**Gap NR4 [mm]:**
61	3_13	Flux-integrated	0,21	0,3
62	3_14 + extra on NR4	Flux-integrated	0,23	0,305
63	3_15	Flux-integrated	0,215	0,31
64	3_16	Flux-integrated	0,23	0,295
65	3_17	Flux-integrated	0,225	0,305
66	3_18	Flux-integrated	0,235	0,295
67	3_16	Flux-integrated	0,215	0,32
68	3_16	Flux-integrated	0,235	0,315
69	3_16	Flux-integrated	0,24	0,31
70	3_16	Flux-integrated	0,23	0,29
Batch 8				
Ex nr:	**Program:**	**Filler material:**	**Gap NR3 [mm]:**	**Gap NR4 [mm]:**
71	1_4	Solid	0,23	0,285
72	1_4	Solid	0,235	0,29
73	1_4	Solid	0,22	0,315
74	1_4	Solid	0,225	0,295
75	1_4	Solid	0,23	0,285
76	1_4	Solid	0,235	0,285
77	1_4	Solid	0,235	0,315
78	1_4	Solid	0,23	0,3
79	1_4	Solid	0,235	0,295
80	1_4	Solid	0,235	0,305
Batch 9				
Ex nr:	**Program:**	**Filler material:**	**Gap NR3 [mm]:**	**Gap NR4 [mm]:**
81	1_4	Solid	0,245	0,29
82	1_4	Solid	0,24	0,315

83	1_4	Solid	0,2	0,3
84	1_4	Solid	0,225	0,295
85	1_4	Solid	0,225	0,315
86	1_4	Solid	0,235	0,29
87	1_4	Solid	0,21	0,295
88	1_4	Solid	0,22	0,33
89	1_4	Solid	0,235	0,295
90	1_4	Solid	0,22	0,315

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