MASTER'S THESIS

Brazing as a Fabrication Method when Manufacturing an Intermediate Compressor Case in Stainless Steel

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Preface

This report is the written recital of our master thesis work. The thesis work is the concluding part of our MSc degree in Mechanical Engineering at Luleå Tekniska Universitet. The thesis work has been carried out on behalf of Volvo Aero Corporation but we have been stationed in Luleå during the course of the work.

The following people have been of great help and value during the course of this thesis work and deserve our gratitude.

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Abstract

Almost every industry of today, aviation industry included, focuses on reducing costs to remain competitive. Volvo Aero Corporation (VAC) manufactures high technology components for jet engines and is a collaborator in numerous commercial jet engine programs. One of these components is the Intermediate Compressor Case (ICC) which is located between the intermediate pressure compressor and the high pressure compressor and is a static, load carrying structure. Compressor structures in aircraft engines are generally cast and made in titanium. This project has investigated how the next generation ICC could be fabricated in the stainless steel 17-4PH by brazing in order to reduce manufacturing cost.

The thesis aims to come up with a solution on how the ICC can be brazed. To achieve a successful brazing operation there are several factors to consider. Brazing filler metals, joint design, joint clearance, non-destructive testing and the complete brazing process with manufacturing solutions for the involved parts has been investigated in this thesis.

A literature study of brazing methods, brazing filler metals, joint designs and furnace types was made in the beginning of the thesis work. Solutions for these stages were categorized in concepts and then selections were made with the aid of comparison tables and evaluation matrices.

The conclusions drawn in this project are that brazing of the ICC is possible as long as the tolerances of the parts are accurately controlled and suggestions on how the tolerances can be controlled are presented in the thesis. The joint proposed is a modified butt-lap joint and the filler metal proposed is the nickel based Ni-613. The final concept advocates that no clearance except the work-pieces surface roughness should be used when brazing the ICC. Guidelines for improving the Technological Readiness Level at VAC are also included in the thesis.

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Nomenclature

Term	Description
VAC	Volvo Aero Corporation
ICC	Intermediate Compressor Case
LTU	Luleå Tekniska Universitet
IPC	Intermediate pressure Compressor
HPC	High Pressure Compressor
NSA	Next Single Aisle
BFM	Brazing Filler Metal
NDT	Non Destructive Testing
LMD	Laser Metal Deposition

1. Introduction

This thesis is a spin-off from the SIRIUS 09/10 project “Development of an Intermediate Compressor Case in stainless steel” performed at Luleå University of Technology together with Volvo Aero Corporation. The emphasis of this project will be on the joining of parts by brazing.

1.1. Background

The aircraft industry of today has a focus on developing more environmental friendly products by making lighter engine parts and decreasing the fuel burn, the focus on cost has also increased due to the competition in the industry. The product investigated in this project is an ICC, see Figure 1. The function of the ICC is to carry axial and radial load and to hold a bearing, air is transported through the ICC from the IPC to the HPC.

Figure 1. ICC - Intermediate Compressor Case.

VAC has designed ICCs for a number of big and medium aircraft engines. The ICC dealt with in this project will be manufactured for a NSA-type aircraft, which means short range flight missions. The ICC is located in the middle of the engine between the IPC and HPC, see Figure 2. VAC will manufacture approximately 1000 ICCs of this type every year.

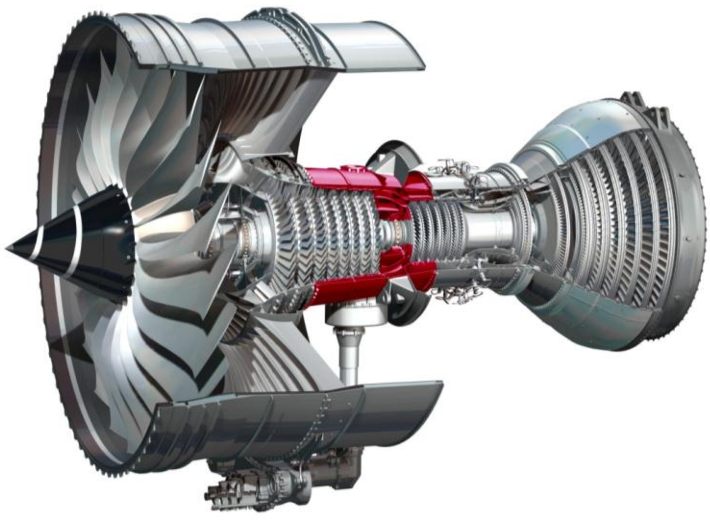


Figure 2. The ICC is located between the IPC and HPC.

Compressor structures are traditionally cast in titanium because of the high Young's modulus compared to the density. The price of titanium has increased, and the suppliers of these complex casts are few. Stainless steel has a Young's modulus/density ratio that is almost the same as titanium; hence stainless steel is able to compete with titanium. Manufacturing in stainless steel enables splitting of the ICC into sub-parts that are joined into the final product. Welding is the commonly used method for joining of stainless steel parts but it has a couple of disadvantages. The main ones are the HAZ, the access demands and the residual stresses.

One of the concepts that made it to VACs final concept selection was the "Spider concept". The main idea of this concept is the split-up of the ICC into two rings and eight boxes, see Figure 3.

Figure 3. The "Spider concept"

The advantage with this concept is that manufacturing of the rings and the boxes will be relatively simple and less expensive compared to some of the other concepts. Welding of this concept was ruled out since it would cause residual stresses due to the large amount of parts that needs to be joined. Instead was brazing was chosen as the manufacturing method since it has the advantage of being able to join all parts in one operation. A brazing operation barely leaves any residual stresses in the joints and the heat applied is lower than that of a welding operation. VAC chose to not continue work on the "Spider concept" despite all of its advantages due to the low Technological Readiness Level (TRL) for brazing at VAC. VAC still wanted to know if the "Spider concept" was possible to manufacture and that is why this thesis work was created.

1.2. Scope

The scope of the thesis work involves the complete brazing process from choosing BFM to investigating the brazed joints. Below follows the major steps in this process and a short description of them.

BFM selection

There are a wide range of BFMs on the market today, for stainless steel the BFMs can be of nickel, silver, gold, copper and palladium type. The demands on the BFM are:

- Ability to work in a temperature of 350°C.
- Ability to withstand corrosion.
- Have a brazing temperature of max 1150°C.
- Produce a joint with the same strength as the base metal.

Joint design

The joint used must be designed to fulfil the strength requirements and it has to be free from irregularities in the aero duct to not cause turbulent air flow.

Proposal for an automated fabrication line

It must be possible to produce 1000 components/year in an automated system. It is important to have low grade of failures and it should be possible to repair inadequately brazed components.

Visualisation of the process

The automated line will be visualised in either a robot simulation software or in a production simulation software.

Geometry assurance

The geometry assurance will be performed at VAC but input to the geometry assurance must be compiled.

Cost analysis

The cost analysis will be made by investigating the operation times on different production concepts. The data can then be used as an input in the evaluation of different concepts.

Evaluation of the brazing method and material test for verification

Tensile testing of suitable joints and BFMs will be made to determine that they can satisfy the requirements.

Investigation of NDT-methods

NDT methods will be studied to decide which type of testing method that can be used to control the quality of the brazed ICC. How the NDT will be conducted in practice will not be investigated.

2. Method

The working process of the thesis work consists of four different steps which are presented below. The steps has been carried out in the order they are presented.

2.1. Planning

One of the first tasks in all projects is to define the scope and adapting it to the time frame of the project. The scope of this project was first presented by VAC as deliverables, see Appendix 3. These deliverables was thoroughly investigated and adjusted to suit the time plan and goals of this project. A preliminary time plan was created from these adjustments.

2.2. Literature study

Much of the information compiled in this thesis work has been collected through a literature study that was performed at the beginning of the project. This information was collected from books, Internet web pages or oral contacts at VAC and LTU. Most of the information presented in this thesis has been verified by the use of multiple sources.

2.3. Concepts

Tables and matrices have been used to ensure that an objective decision has been made every time there has been a choice between two or more technical solutions. This method presents the necessary information in a lucid way and makes it easier to come up with an objective decision.

2.4. Verification/visualization

Verification of the different concepts has been carried out in different ways depending on which subject they treat. A tensile test was supposed to be made to investigate BFMs and joint clearances while the reach and access for welding equipment was verified and visualized by using UGS NX 7.5.

3. Brazing theory

Brazing is a metal-joining technique where the work-pieces are joined by a BFM with a lower liquidus than the base materials. The biggest difference between welding and brazing is that the base material is melted in welding, while brazing only melts the BFMs. Brazing is carried out in a temperature exceeding 450°C otherwise the correct term for the method is soldering. Another difference between soldering and brazing are the bonds formed, brazing forms metallurgical bonds while soldering produces mechanical bonds. It is important that the work-pieces are closely fitted before brazing due to capillary action drawing the BFM into the joint. Usually the brazing process takes place at a temperature around 50°C above the BFMs melting point thus melting the filler material which then covers the mating surfaces. [1]

There are several advantages with brazing in comparison with welding, some of the advantages are:

- Economical for fabrication of complex assemblies and assemblies with many components
- Easy to obtain large joint area or long joint length
- Very good stress distribution and heat-transfer properties
- Capable of preserving protective metal coating
- Possible to join cast material to wrought metals
- Ability to join dissimilar materials
- Possible to join metals with varying thickness

Part's that cannot be joined with other methods is often possible to join with brazing. Brazing joints is well suited for making complex assemblies with odd shapes and varying thickness. When the joints are made it is important to keep the tolerances close otherwise the capillary attraction will not draw the BFM into the joint. Another problem with brazing is that the brazed joint is not homogenous, the boundary zone has different chemical and mechanical properties compared the base metal. For example some BFMs make the joint more corrosive or brittle. [1]

3.1. Capillary flow

Capillary flow is one of the most important parameters in brazing. Capillary attraction means that the base metal wants to draw the BFM into the joint gap between the parts; this is caused by attraction between the molecules in the BFM and the base metal. There are several parameters that influence the capillary flow including; fluidity, viscosity, vapour pressure, gravity and metallurgical reaction between the base metal and the BFM. When the joint is accurately spaced and designed the molten BFM is drawn through the joint gap without producing any voids. [2]

3.2. Wetting

To achieve good flow the BFM has to be able to wet the base metal. Wetting means that the adhesion between the base metal and the molten BFM is greater than the liquids cohesive force. In practice it means that the BFM spreads on the surface. The filler metal has to be able to dissolve into, or alloy with the base metal. The capillary space in the joint has to promote wetting otherwise the filler metal will not be drawn in with capillary attraction. Oxide layers and contaminated surfaces prevent wetting, making it important to keep the joint clean. [1]

3.3. Heating methods

There are numerous heating methods available for brazing. The choice of the most suitable method is affected by many different factors. The most important are:

- Size of assembly
- Production rate/quantity
- Access
- Type of heating
- Heating/cooling rate
- Capital cost

3.3.1. Torch

The simplest braze heating method is manual torch brazing. The most common way to perform this is by a hand-held torch in one hand and the BFM rod or wire in the other. This can be used to perform repairs, one of a kind brazing jobs or small-scale production. Torch brazing may also be automated by using several machine-mounted burners; this setup can produce up to a couple of hundred assemblies every hour. Torch brazing is widely used because of its relatively low costs and portability. The method resembles welding with the main difference being that only the base metal is heated during brazing while the filler metal is heated during welding. [1], [4]

3.3.2. Furnace

One of the most commonly used brazing methods is furnace brazing. The popularity originates from its many advantages such as:

- Minimal fixturing
- Adaptability of the furnace
- Simultaneously brazing of multiple joints
- Highly repeatable
- Option of integrating heat treatment
- Controlled atmosphere

Furnace brazing is a medium- to high-volume process where the BFM needs to be preplaced near or in the joint. The assembly can either be self-fixturing, fixtured in the furnace or tack-welded before going into the furnace. Distortion is avoided in furnace brazing due to the gradual and homogeneous heating. Flux is used except when reduced atmosphere, such as hydrogen or vacuum, and exothermic or exothermic combusted gas are used in the furnace. Hydrogen furnaces are filled with H_2 molecules that react with the metals oxide layer forming H_2O, vacuum furnaces prevents oxides from forming by keeping the atmosphere free of O_2 molecules. The atmosphere to use in the furnace is decided by the base material and filler material. The disadvantages of furnace brazing:

- Relatively high capital cost
- High power consumption

- Maintenance requirements
- Environment and safety considerations

Brazing furnaces may be gas-fired or electronically heated, but the most commonly used way to transfer heat to the work piece is by electrical radiant heating elements. The design of the furnace can vary from manually loaded to atmosphere controlled mesh-belt conveyor types. Though for high-volume production, the most popular type is the continuous furnace with conveyor belt. This type of setups often comes with several different temperature zones to provide preheating, brazing and cooling, see Figure 4. The assembly needs to be properly supported so it can withstand the movements of the conveyor belt, this can be done by self-fixturing in most cases. [1], [5], [6]

Figure 4. Continuous furnace with conveyor belt

When it comes to small volumes and high value products it might be more suitable to use a manually loaded batch furnace. A batch furnace can be loaded from the top, bottom and the side. The batch furnace has a chamber and the object is inserted and withdrawed though the same door, see Figure 5. The chamber is usually cooled by pumping in argon when the brazing is completed to get a fast cooling rate down to room temperature. A batch furnace can handle large assemblies. [1]

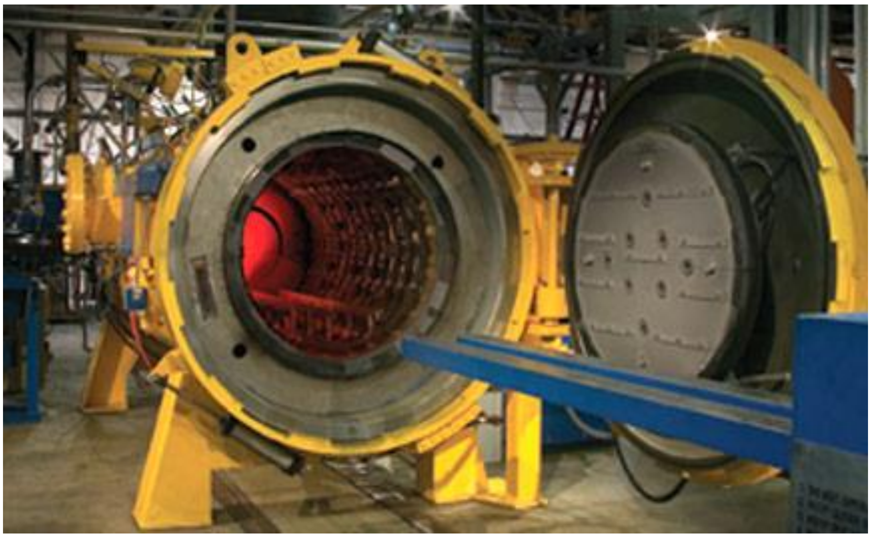


Figure 5. Batch-type furnace of vacuum type

3.3.3. Induction

Induction brazing is carried out by inducing electric current into the parts that will be brazed together. The coils that induce the current are water-cooled. BFM must be preplaced and the design of joints and coils are critical to make sure the joints reaches brazing temperature at the same time. [7]

Induction brazing is suitable when rapid heating is required and the method is ideal when good temperature control is desired. It is possible to braze in sequences and to control which parts to heat making it possible to only heat the joint areas and keep the rest of the component in room temperature. Induction brazing is difficult to use when the assemblies are complex. The investment cost is also high and the fixturing is more difficult than in a furnace [3]

3.3.4. Infrared

Infrared brazing is a type of furnace brazing where the difference is that the heating occurs by infrared radiation from high-intensity quartz lights. The time and temperature in infrared brazing can be controlled down to fractions of degrees and seconds. Reflectors and parabolic focuses is used to control the heat in the furnace. The lamps can reach a power output of 5000 W making it faster than a traditional furnace. [1]

3.3.5. Heating method selection

The demands on the brazing operation are that it must be carried out in a controlled atmosphere, the heating source must be able to emit heat on the joint and the brazing operation must be automated. The complex geometry therefore rules out torch brazing and induction brazing because the brazing equipment cannot reach the joint, see Table 1.

Table 1. Characteristics of heating methods

Method	Characteristics					
	Capital cost	**Usage cost**	**Flux required**	**Production rate**	**Complex geometry**	**Feasible sizes**
Torch	Large	Medium/High	Yes	Medium	Low	Large
Furnace (atmosphere)	Medium/High	Medium/High	Yes/No	High/Low	High	Large
Furnace (vacuum)	High	Low	No	High/Low	High	Large
Induction	Medium/High	Medium/High	Yes/No	Low	Medium	Medium
Infrared	Medium	Low	Yes/No	Low	High	Medium

Due to the constraints, a furnace must be used for brazing the ICC, leaving furnace brazing and infrared brazing as the only options. The advantage with an infrared furnace is that it is faster than a traditional furnace and the heat can be distributed where it is desired. Since the time for a brazing furnace in comparison with an infrared furnace is negligible when the production rate is 800-1000 components/year, furnace brazing has been selected as the method for brazing the ICC. Also a furnace has uniform heat and thus permitting the heat treatment to be performed in the same production step as the brazing. By using furnace brazing the steps in the production cycle can be minimized by brazing the whole assembly in one step. The furnace type chosen is a batch vacuum furnace since VAC uses vacuum furnaces for heat treatment and has extensive knowledge about these types of furnaces.

3.4. Brazing in stainless steel

Stainless steels are usually not difficult to braze except for the alloys containing titanium or aluminium. Brazeability varies among the steels due to different compositions of the alloys. The high chromium content in stainless steel creates a film of chromium oxide on the surface which then prevents the wetting of the base metal. When stainless steel is heated the chromium oxide is formed more rapidly. The flow of the BFM can also be influenced by contaminants from e.g. lubricants. There are several ways to assuage the negative effects of the oxide layer:

- Using flux.
- Using BFMs with a low melting point.
- Chemically or mechanically removing the chromium oxide before the brazing operation.
- Braze in hydrogen or vacuum atmosphere.

All conventional brazing techniques can be used to braze stainless steel but furnace brazing is the most commonly used method because most applications require vacuum or hydrogen atmosphere.

BFMs are chosen with respect to mechanical properties, corrosion resistance, service temperature and compatibility with the base metal. Almost all types of stainless steel can be brazed with the nickel-, copper- and gold-based BFMs. [8]

3.5. Residual stresses

FEM-simulation of a brazement between 2 mm thick sheets with a butt-lap joint has been conducted by Pahkamaa. The materials used in the simulation are steel as base metal and aluminium as BFM. Pahkamaa concludes that the residual stresses in brazing are relatively small (maximum of 11,5 MPa) and that a smaller difference in thermal expansion coefficient between the metals will produce even smaller residual stresses. [9]

4. Brazing Filler Metals

A BFM is the metal that is melted in order to join parts together in brazing; the BFM must therefore have a melting point lower than the work metals. BFMs can be delivered in several different forms, including: paste, wire, foil and preformed wire. The most important aspects to take into consideration before choosing BFM are:

The base metal being joined
The brazing process can differ greatly depending on the base metal being brazed. Special consideration must be taken when two dissimilar material are being joined.

The heating method to be used
BFMs with melting ranges of less than 25°C between the solidus and liquidus phase can be used with any heating method. Liquation happens when one constituent of the BFM melts before the other, this is common when the BFM has a long melting range and the component is heated slowly through the melting range. BFMs that tend to liquate needs a heating method that can raise the joint temperature rapidly or allows the BFM to be introduced after the base metal reaches the brazing temperature.

Service requirements
The BFM must withstand the operating requirements of the assembly such as service temperature, thermal cycling, corrosive conditions and life expectancy.

Price of the BFM
Precious BFMs might have advantages over some of the cheaper BFMs but may be excluded due to the elevated price.

4.1. Commonly used elements

There are almost endless possibilities of combinations of elements when designing a BFM and it is necessary to know how each element affects the brazing process. The most commonly used elements in BFMs for vacuum furnace brazing of stainless steel are presented below.

4.1.1. Nickel
Nickel produces strong and corrosion resistant joints but it tends to prevent flow of the melted BFM. It can endure high temperature service and needs alloying additions of elements such as boron, carbon, chromium or manganese to lower its melting point. [10]

4.1.2. Gold
Gold is very expensive but has excellent corrosion resistance and can wet most materials; it has a low rate of interaction with the base metal which makes it suitable for brazing of thin sections. Gold are generally suitable for continuous service at 425°C and intermittent service at 540°C depending on the operating environment. [11]

4.1.3. Silver

Silver offers excellent capillary flow but is not suitable for vacuum brazing. It reduces the melting point of most alloys. [10]

4.1.4. Palladium

Palladium possesses many of the beneficial properties of the gold BFMs, but at a lower price. It has good corrosion resistance although not as good as the gold-bearing brazing alloys. Palladium provides higher mechanical strength at elevated temperatures than gold-bearing alloys. Palladium does not form brittle intermetallics. [12]

4.1.5. Chromium

Chromium increases the strength, ductility and corrosion resistance but the downside is that it impairs wetting of gold/nickel alloys, this can be compensated by additions of boron or phosphor. [10]

4.1.6. Boron and phosphor

Boron and phosphor lowers the melting point of most metals and at the same time it increases the wetting characteristics of nickel-base brazes. They rapidly diffuse into the base metal, which might cause intergranular embrittlement and will therefore greatly decrease the joint ductility. The rapid diffusion will also increase the remelt temperature, allowing the BFMs to be used for step brazing. [12]

4.2. BFM example

Au-22Cu-8.9Ni-1Cr-0.1B is a good example of how different elements can work together to make an applicable BFM. This gold-based BFM was designed for fluxless vacuum brazing of stainless steel. With a continuously rising gold price it is desirable to keep the gold content as low as possible. This was done by substituting the gold with nickel and copper. Adding chromium compensated for the undesirable deterioration of oxidation resistance caused by the addition of copper. The chromium in turn impaired the wetting characteristic, which was compensated by adding a small amount of boron. The relative proportions of every elements were finally adjusted to minimize the melting range, while optimizing the mechanical properties. [11]

4.3. Selection criteria

When selecting BFM there are several factors to consider. The chosen BFM must be able to form a joint with required strength, ductility, toughness, temperature resistance, erosion resistance, corrosive resistance and stability. It is beneficial if the thermal expansion coefficient of the BFM matches the base metals to avoid the forming of residual stresses in the joint. The BFMs brazing temperature must be lower than the melting temperature of the base metals but higher than the service temperature of the application.

The chemical compatibility between the metals must be considered to avoid corrosion. BFMs must be able to wet the base metal and fill the gap to produce strong joints and avoid reactions causing a brittle phase. The price differs greatly between filler metals and it is important to consider if the benefits of using a more expensive filler metal is worth the increased cost.

4.4. Selection

A list of suitable BFMs has been compiled to aid the selection, the BFMs on the first list were chosen because they are compatible with stainless steel and can withstand a service temperature over 350°C. The list can be found in Appendix 1.

For the last selection the list was narrowed down to the seven BFMs that best meet the demands. A matrix with nine different evaluation parameters was constructed as a support for the choice of BFM. The nine evaluations parameters where weighted against each other to get an as objective and correct result as possible. The weighting was done by comparing the parameters one by one and giving them a total of two points, see Table 2. The parameter that was considered to be of greater importance was given two points and the parameter of less importance was given zero points. If the parameters was of the same importance one point was given to both. As an example, brittle phase was considered to be of greater importance than the brazing temperature and was therefore given two points. This meant that the brazing temperature was given zero points in comparison to brittle phase. The sum of each parameters points was divided by the total sum of all parameters points to get a normalised weight. [13]

Table 2. Weighting matrix

	Brittle phase	Erosion	Corrosion	Tensile strength	Brazing temperature	Wetting	Liquation	Gap filling	Price
Brittle phase	1	1	0	0	2	2	2	1	1
Erosion	1	1	0	1	2	1	2	1	0
Corrosion	2	2	1	2	2	1	2	2	2
Tensile strength	2	1	0	1	2	1	2	1	1
Brazing temperature	0	0	0	0	1	0	1	0	0
Wetting	0	1	1	1	2	1	1	2	0
Liquation	0	0	0	1	0	1	1	1	0
Gap filling	1	1	0	1	2	0	1	1	0
Price	1	2	0	1	2	2	2	2	1
	0,12	0,11	0,20	0,14	0,02	0,11	0,05	0,09	0,16

The most important evaluation parameters according to Table 3 are the corrosion resistance and the price of the BFM. The ability to avoid brittle phase and the tensile strength of the BFM are also of major importance.

The nine evaluation parameters were then used in the final evaluation matrix. The seven BFMs were given a number between 1 and 5 where 5 is best and 1 is worst. Each number was multiplied with the corresponding weighting factor, see Table 3. The multiplied numbers from each row was added together to give each BFM a total sum that could be used to compare the BFMs with each other.

Table 3. Evaluation matrix

BFM	Brittle phase	Erosion	Corrosion	Tensile strength	Brazing temperature	Wetting	Liquation	Gap filling	Price	
	0,12	0,11	0,20	0,14	0,02	0,11	0,05	0,09	0,16	
BAu-4	5	5	5	5	4	4	5	2	0	3,80
BNi-2	2	5	4	5	3	4	4	2	4	3,80
Ni-613	5	5	5	3	3	5	4	5	4	4,47
Palnicro-30	4	5	5	5	5	4	4	2	0	3,65
BrazeLet-F300	4	4	4	2	2	5	4	4	5	3,95
AMS 4764	5	4	3	4	4	3	4	2	4	3,64
Hi-temp 870	5	2	4	3	3	5	3	5	4	3,89

The information about the BFMs is taken from standards and suppliers websites. Suppliers include Morgan Technical Ceramics Wesgo metals, Höganäs, LucasMilhaupt and Johnson Matthey. These seven filler metals were chosen because they best satisfied the demands. Ni-613 got the highest score by far and was therefore chosen as one of the BFMs to test in the material test. The other BFM that was chosen is the BNi-2 because VAC has used it before and it is a common BFM for these applications, this makes it a good reference to the Ni-613 BFM. Palnicro-30 and BAu-4 got a 0 in the "Price"-category since the price for these BFMs are much higher than the other BFMs and considered too expensive. [14], [15], [16], [17], [18], [19], [20]

5. Joint design

When designing a brazed joint there are several factors to take into consideration, the most important ones are:

Capillary attraction
Almost all brazing methods depend on capillary attraction for the distribution of the molten BFM and a properly designed joint with the correct clearance for the selected BFM increases the capillary attraction.

Strength of the BFM
The BFM has, in general, lower bulk strength than the base material. To compensate for this the contact length of the joint is increased up to a certain length when a longer joint stops giving better strength, usually around 3-4 times the thickness of the parts that are brazed. This usually gives a joint of higher strength than that of the base metal.

Type of stress
The most preferable type of stress in a brazed joint is in general shear stress rather than tensile stress. A butt joint is usually exposed to tensile stress while the lap joint is exposed to shear stress.

5.1. Type of joints

There are basically only two different types of joint when it comes to brazing, butt joint and lap joint. All other joints are modifications of these two. The most common joint designs can be seen in Figure 6.

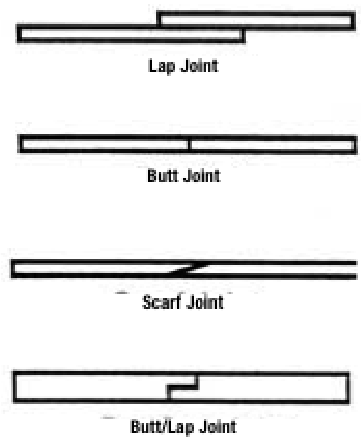


Figure 6 Typical joints used when brazing

5.1.1. Butt joint

The butt joint has two main advantages, the single thickness of the joint and the simple preparation. However, in most cases the advantages are overshadowed by the fact that a butt joint has minimal bonding area. The small bonding area in combination with almost all of the loads transmitting as tensile strength makes this joint design unwanted in all high strength requiring designs. [1]

5.1.2. Lap joint

The bonding area of a lap joint can easily be increased to fulfil the strength requirements of the design. The optimal length of the lap joint can be calculated by considering the strength of both the BFM and the base metal. The major disadvantage with the lap joint is the increased thickness of the joint. [1]

5.1.3. Joint length

The strength of a brazed joint depends on the length of the joint. A formula for calculating the optimal joint length exists:

$$X = \frac{TW}{CL}$$

X is the joint length, T is the tensile strength of the weakest member, W is the thickness of weakness member, C is the safety factor (usually 0.8) and L which is the shear strength of the BFM. The shear strength of the BFM can be very hard to find since most BFM manufactures does not specify this information. Three times the thickness of the thinnest member has been used during this project to ensure that the joint strength surpasses that of the base metal. [1], [28]

5.2. Joint design for the ICC

The ICC concept studied in the thesis consists of thin-walled work-pieces, some of the walls form an aero duct and hence the walls must be free from irregularities to not cause turbulence. The design space is therefore constrained for the joints; the different concepts for the joint designs are presented below.

5.2.1. Concepts

Concept #1

Concept #1 is a traditional butt-lap joint where the thickness of the rings and the box are equal. The advantages with his type of joint are that the shearing of the joint is minimized and the fitting helps fixture the component. Another advantage is that this type of joint does not increase the weight of the component. This concept requires machining of both components and this can be hard to perform on thin walled parts. The joint is shown in Figure 7.

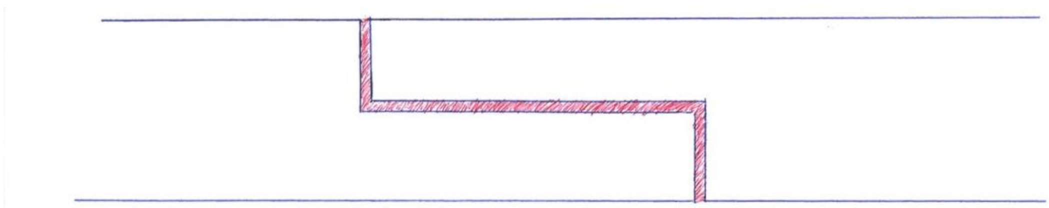


Figure 7. Traditional butt-lapp joint

Concept #2

In Concept #2 the rings are thicker than the box and the rings are machined to make the boxes fit, see Figure 8. The uneven side is positioned where no airflow is required. The cutout will act as fixturing of the box. Generally machining is not required on the boxes with this type of joint. The addition of weight due to the increased thickness of the rings can be calculated by multiplying the increased volume with the density of stainless steel (7900 kg/m^3). The increased thickness (t) is one millimeter, the width of the increased thickness is estimated as five millimeters and the total length of each joint is 700 millimeters. Two rings and eight boxes give a total of 16 joints.

$$\Delta m = \Delta V \times \rho = \Delta \mathrm{t} \times \mathrm{w} \times \mathrm{l} \times 2 \times 8 \times 7900 = 0{,}001 \times {\sim}0{,}005 \times 0{,}700 \times 16 \times 7900 \approx 0{,}4424\mathrm{kg}$$

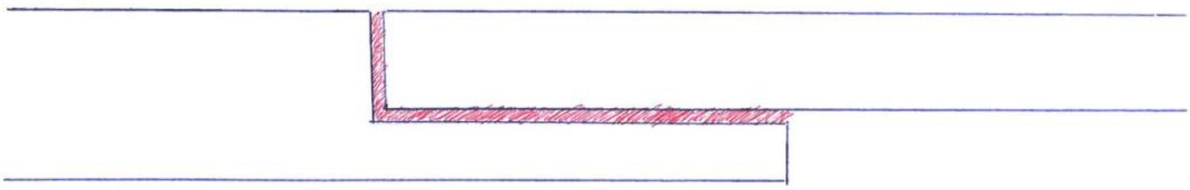


Figure 8. Joint design with a cutout on the ring

Concept #3

In the third concept the box and the rings are equally thick and a third sheet is added to make the joint, see Figure 9. The length of the added sheet must be 6x the thickness of the box and the rings. The advantage with this concept is that no cutout has to be made, however another part is added to the joint possibly making the brazing more complex. This joint also increases the weight of the component. The weight addition can be calculated in the same way as Concept 2. The thickness, length and density are the same as Concept 2 but the joint width is 12 millimetres.

$$\Delta m = \Delta V \times \rho = \Delta \mathrm{t} \times \mathrm{w} \times \mathrm{l} \times 2 \times 8 \times 7900 = 0{,}001 \times 0{,}012 \times 0{,}700 \times 16 \times 7900 = 1{,}06176\mathrm{kg}$$

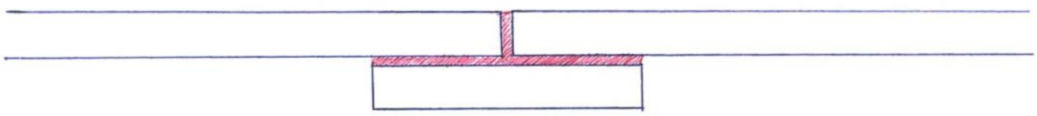


Figure 9. Joint design with an additional sheet

5.2.2. Concept selection

Concept #3 is the best concept from a pre-machining point of view but the more complex fixturing and the need of using twice the amount of BFM makes it a less desirable choice, because of both the cost of the BFM and the risk of an inadequately brazed joint. The properties of Concept #1 and Concept #2 are the same with the exception of the machining needed, see Table 4. Concept#1 is the preferable choice if it is possible to manufacture with good results due to the lower weight compared to Concept#2 and Concept#3. Concept#1 requires the joint area to be milled from two millimetres thickness down to one millimetre on both the rings and the boxes. This is not a preferable operation, hence is Concept #2 the winning concept.

Table 4. Joint design selection

	Concept #1	Concept #2	Concept #3
Machining needed	Both on the rings and boxes.	Only on the rings.	No machining
Complexity of brazing	Design helps fixturing.	Design helps fixturing.	Extra component, harder fixturing than the other.
Joint length	Standard	Standard	2x standard
Additional weight	None	~0,44 kg	~1,06 kg

5.3. Joint clearance

The strength of a joint depends mostly on the clearance between the joined parts. All BFMs have an upper limit for how large the joint clearance can be, there is a risk for none uniform spreading if the clearance surpasses that limit. However, it is recommended to keep the clearance as tight as 0.05 mm since tighter clearance gives higher joint strength and it is a popular belief that any lower clearance will impair the flow of the BFM, see Figure 10.

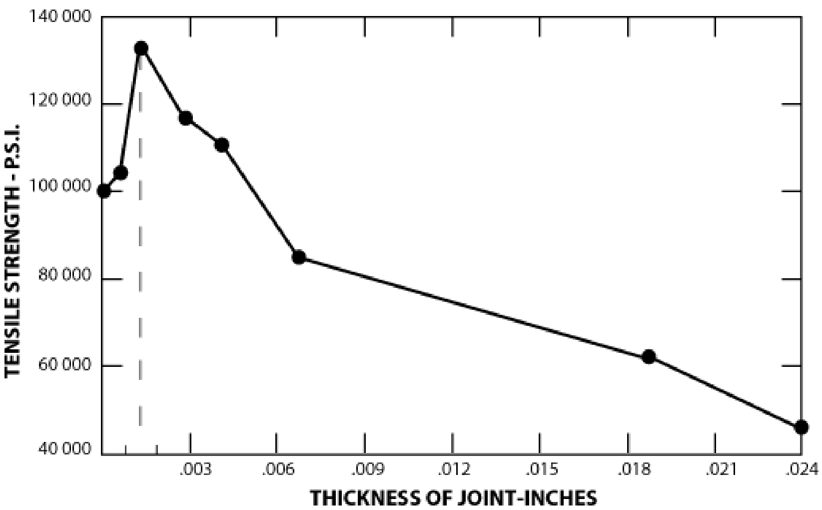


Figure 10. Tensile strength compared to joint clearance

According to Dan Kay, the chart from Figure 10 derives from a test done in the late 1930s. This test was performed with torch brazing together with flux which is the reason for the decreased strength of zero clearance joints. Dan Kay also notes that the tensile strength should continue to increase with the lowering of joint clearance if the test were performed in an atmosphere environment. If this is to be true, then brazing with zero joint clearance would give the highest possible tensile strength and at the same time substantially simplify the fixturing. The zero joint clearance is possible due to the roughness of the mating surfaces. The actual contact between the surfaces can be as low as 1%, giving the BFM enough space to spread through the joint area, see Figure 11. [21]

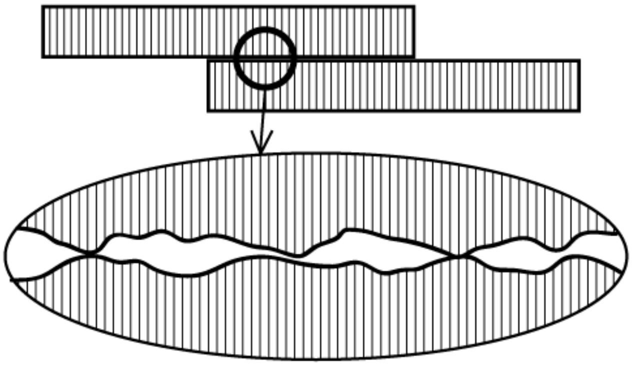


Figure 11. Actual contact between two surfaces

Dan Kay states:

Since the suggested ideal clearances for just about all the BFMs, when operated in an atmosphere (vacuum is considered as an atmosphere) is on the order of about 0.000" – 0.002" (0 – 0.050 mm) total, as mentioned earlier in the article, assembly of parts need not be difficult, nor is it really necessary to provide "spacers" to keep the faying surfaces apart. The normal surface roughness already does that. And, experience over many years by many companies in industry has shown this to be correct. [21]

6. Tensile test

A tensile test was supposed to be performed to verify that the chosen joint design can fulfil the strength requirements. The results from the test were also supposed to assist in the choice of BFM and joint clearance. Two BFMs; Ni-613 and BNi-2 along with three different joint clearances; 0,10 mm, 0,05 mm and 0,00 mm were to be used during the tensile test. 0,10 mm was chosen as a reference, 0,00 mm was chosen to verify that Dan Kays statement about the joint clearance is correct. A sample size of four was to give a total of 24 tensile test pieces. The joint preparation was performed at LTU, the brazing was executed at VAC while Erlandssons were supposed to perform the cut out and Metcut were to do the actual tensile test.

6.1. Joint preparation at LTU

Six water-jet cut sheets were delivered by VAC to LTU. These sheets were then cut into twelve pieces and joint prepared by “Centralverkstaden” at LTU, see Figure 12. The pieces were polished with abrasive paper to remove the oxide layer and cleaned with acetone to remove the grease prior to the tack-welding.

Figure 12. Joint prepared test pieces

A fixture was then used to hold the pieces in a fixed position so it could be tack-welded, see Figure 13. Two different shims were used to give the correct joint clearance. No shims were needed for the 0 mm joint clearance.

Figure 13. Fixture for tack-welding

The tack-welded test piece sheets were attached to a steel plate in an upright position by welding, see Figure 14. This was done to enable brazing of all test piece sheets in one braze cycle. The upright position better represent how the joints of the ICC will be positioned during brazing. The joint area of every test piece sheet was wrapped in plastic to shield it from contaminations.

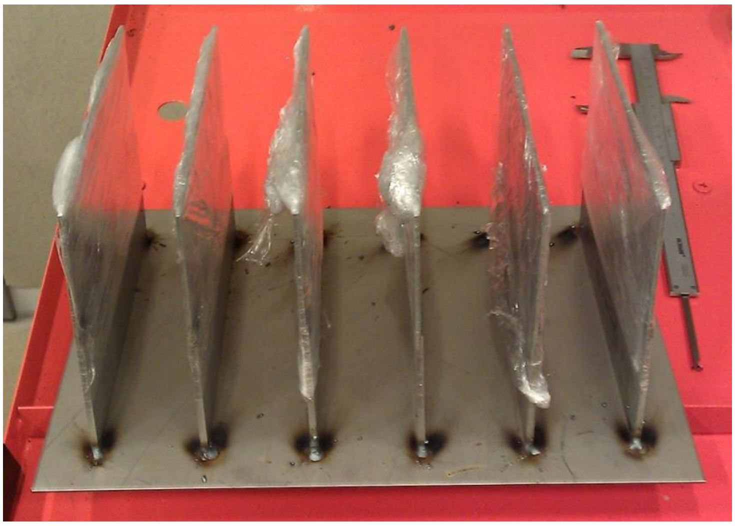


Figure 14. Test pieces ready for furnace brazing

6.2. Brazing at VAC

The area next to the joint was cleaned with acetone to ensure that no contaminations could enter the joint clearance. BFM paste was then applied on the joint prepared side of the test piece sheets. The amount of BFM was adapted to the joint clearance of the test piece sheet. A furnace with a working area of 770 mm x 580 mm x 450 mm was used for the brazing operation. The following brazing cycle was used:

1) The furnace is pumped to a vacuum level of $1x10^{-5}$ torr.
2) The furnace is heated from room temperature to 450°C at a rate of 6°C/min.
3) Held for 10 min to allow the temperature of the load to equalize to the furnace temperature.
4) Heated to 700°C at a rate of 6°C/min.
5) Held for 1 min.
6) Heated to 950°C at a rate of 6°C/min.

7) Held for 1 min.
8) Heated to 1050°C at a rate of 4°C/min.
9) Held for 10 min to allow the BFM to spread through the joint area.
10) Cooled to 950°C at a rate of 4°C/min.
11) Force cooled to room temperature by backfilling the furnace with argon.[22], [23]

The test piece sheets were then supposed to be cut loose from the holding sheet. Unfortunately, the brazing of the test pieces failed due to inadequate tack-welds. Some of the tack-welds that attached the test piece sheets to the holding sheet detached during the latter part of the brazing cycle, this released the residual stresses that were built into the joints, causing the whole setup to vibrate. The vibration in turn caused the BFM to splatter all over the setup and mainly over the holding sheet, leaving no BFM to enter the joint area, see Figure 15.

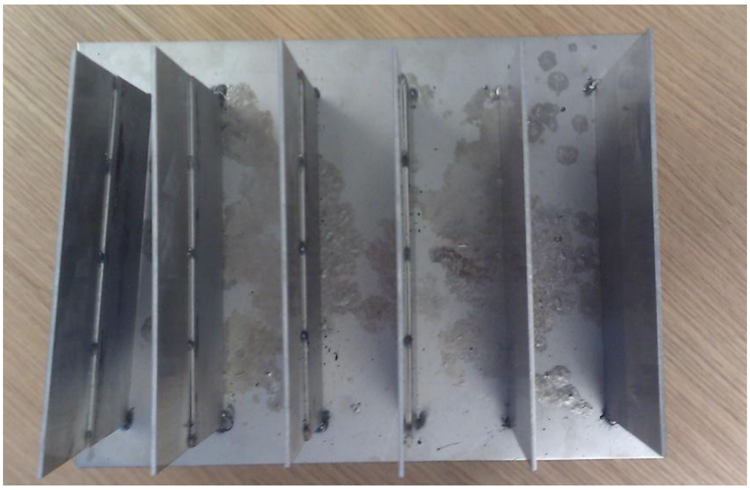


Figure 15. Failure during the brazing operation

6.3. Analysis of the failed brazed joints

Even though most of the BFM was thrown away from the joint area, some of the BFM managed to enter and fill the joint. The tensile test sheets were removed from the ground plate and then s between each tack-weld. This visualized how far the BFM had spread into the joints, three of the plates turned out to have partially filled joints and it was therefore decided to investigate them further by the use of microscopic images. The three plates with acceptable brazing results were:

- 0 mm clearance brazed with Ni-613
- 0 mm clearance brazed with BNi-2
- 0,05 mm clearance brazed with Ni-613

The joint area of the test pieces were sectioned into 10x10 mm samples. The samples were then mounted together into a polymer to make them easier to handle, see Figure 16. The polymer was then grinded and polished to remove most of the scratches.

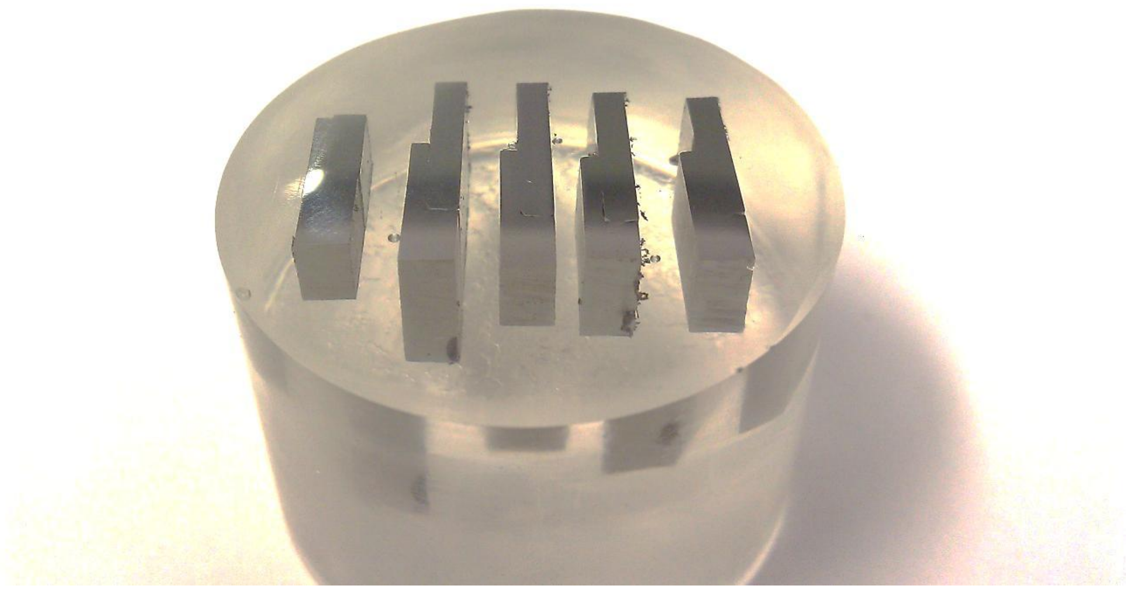


Figure 16. Mounted test pieces

The mounted test pieces were then investigated by the use of a microscope. Figure 17 shows the filled joint in the test piece where Ni-613 is the BFM and there is no joint clearance.

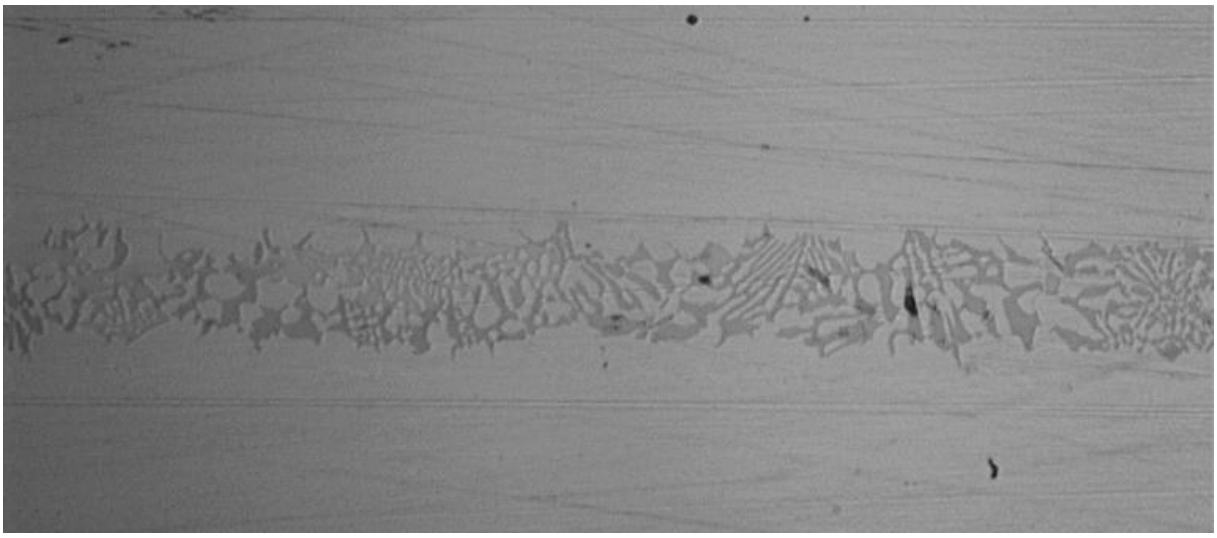


Figure 17. Ni-613, 0 mm joint clearance

Figure 18 shows the joint when BNi-2 is used as BFM and the joint clearance has been 0 mm.

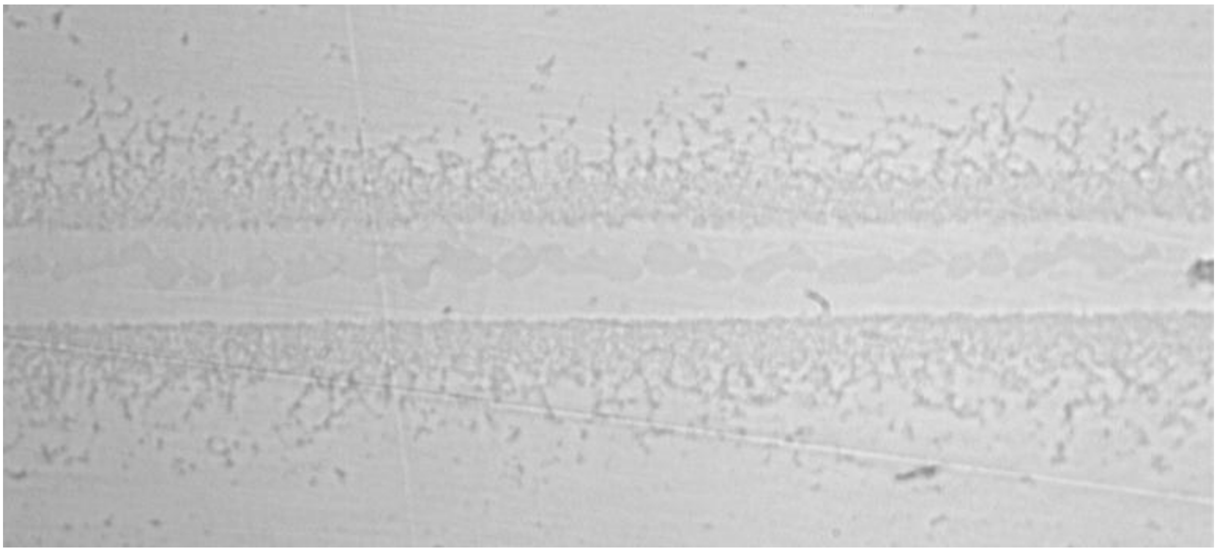


Figure 18. BNi-2, 0 mm joint clearance

As can be seen above, there is a clear difference between the two samples and even though no conclusions about the joint strength can be drawn from the visual inspection, it is apparent that the BFM has filled the joint despite the absent joint clearance. Also it looks like BNi-2 has reacted with the base metal while the transition between Ni-613 and the base metal is hard to discover, the only detail that gives away the joint are the darker areas. More pictures from the microscopic inspection can be found in Appendix 5. There the shortage of BFM in the tests can be observed along with the difference in appearance between the joints and the sheets.

6.4. Future testing

The failure could have easily been avoided by adding a couple of extra tack-welds on every test piece sheet. The reason that this was not performed on this tensile test was due to the limited size of the test piece sheets, see Figure 19.

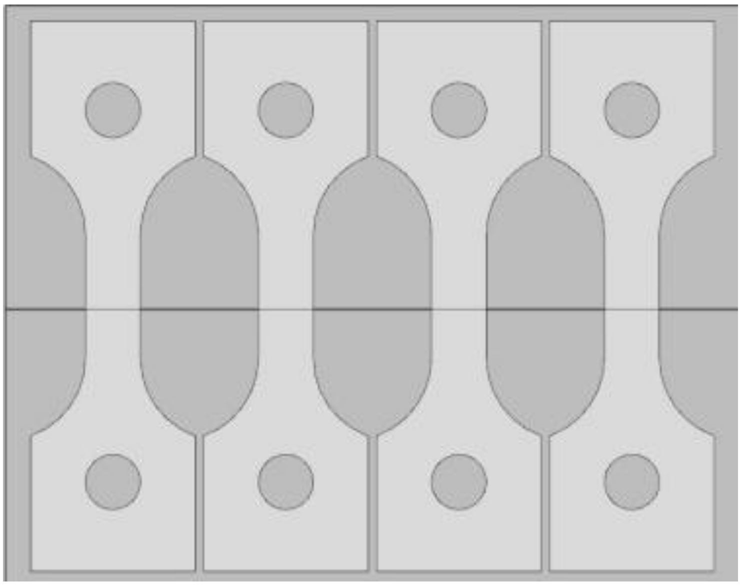


Figure 19. Sheet with test pieces

Another option could be to manufacture a holding plate with tracks in which the test piece sheets could be placed, see Figure 20. A disadvantage with this concept is the increased manufacturing cost and weight but it can be used for more than one brazing operation.

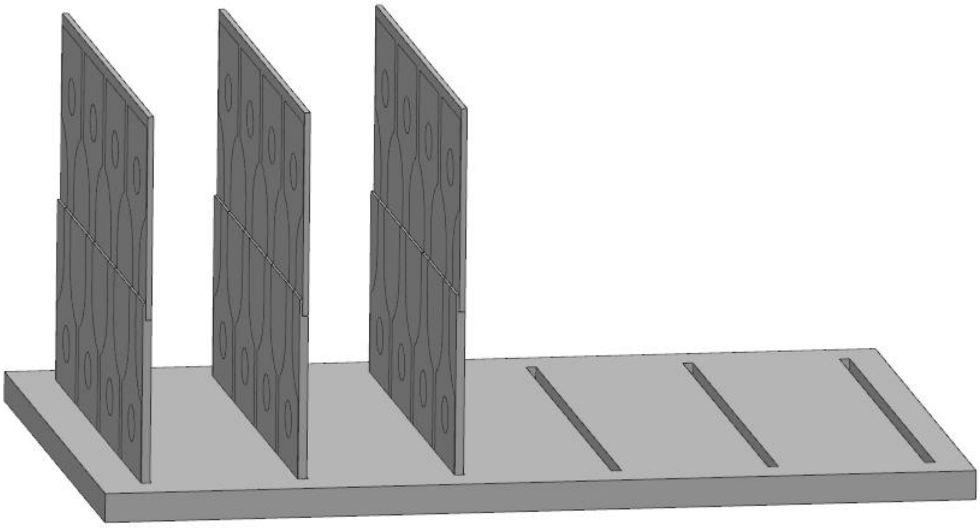


Figure 20. Holding plate with tracks

The use of shims to create the correct joint clearance was perhaps not the best option, the shims were hard to place correctly and the burr created when cutting the shims was a potential source for error. An alternative could be to integrate the clearance into the joint preparation operation by leaving the clearance at five places, see Figure 21.

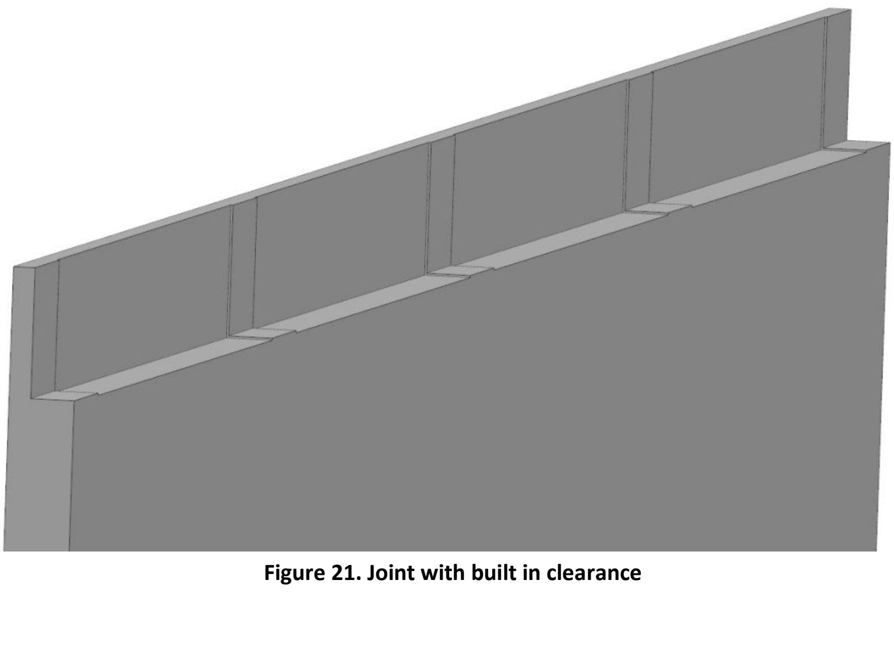


Figure 21. Joint with built in clearance

7. Production

The scope of this project includes the processes before, during and after the brazing operation. These processes are:

- Manufacturing of front ring, aft ring and the eight boxes
- Joint preparation
- Pre braze cleaning
- Fixturing
- Brazing
- NDT
- Repairing
- Heat treatment

The production level of the ICC can be classified as small volume production with a rate of only 1000 ICCs per year but it is still a large volume for VAC, hence the aim is to automate the manufacturing processes as much as possible. The initial conditions for the manufacturing are that the rings will be forged and machined while the boxes will be warm-pressed by a supplier.

Both rings will be delivered as forged pieces. They will be turn-milled and milled into final shape and tolerances. The milling operations should be done in as few setups as possible to ensure tight tolerances and reduce manufacturing time. The tight tolerances are particularly important on the joint area where the brazing will be performed. The surface of the joint area must be kept free from irregularities to insure good brazing results. Irregularities can result in unacceptably large joint clearance between the two mating surfaces.

7.1. Concepts for box manufacturing

There are several ways to manufacture the boxes, but none of the options is particularly desirable, as the joining of the three suggested parts will provide challenges. The box is shown in Figure 22.

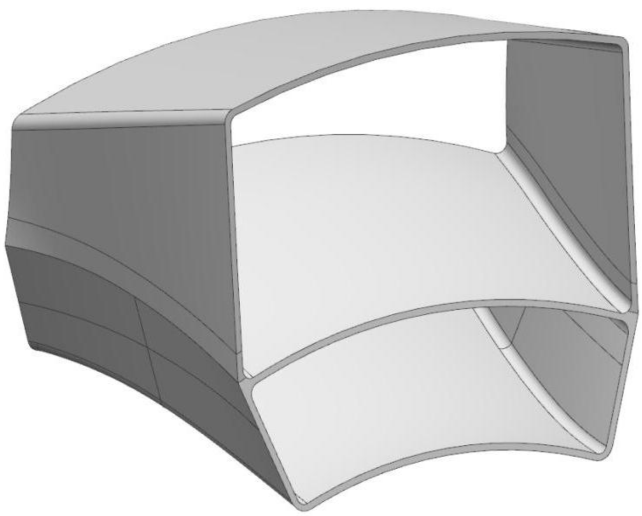


Figure 22. Finished box

The box manufacturing presents some obstacles since the boxes will be pressed. The parts must be designed to have an angle of release of over 95% to not stick to the tools after pressing which implies that the box has to be manufactured in several parts and then joined. Four different manufacturing concepts have been developed for the boxes:

7.1.1. T-weld

The boxes are pressed in three parts and then t-welded where the three parts meet each other, see Figure 23. With this concept it is possible to press all parts at the supplier and then join them with either two or four welds. The T-weld concept provides easy manufacturing since all parts can be pressed. The welding can be problematic since a t-weld is needed.

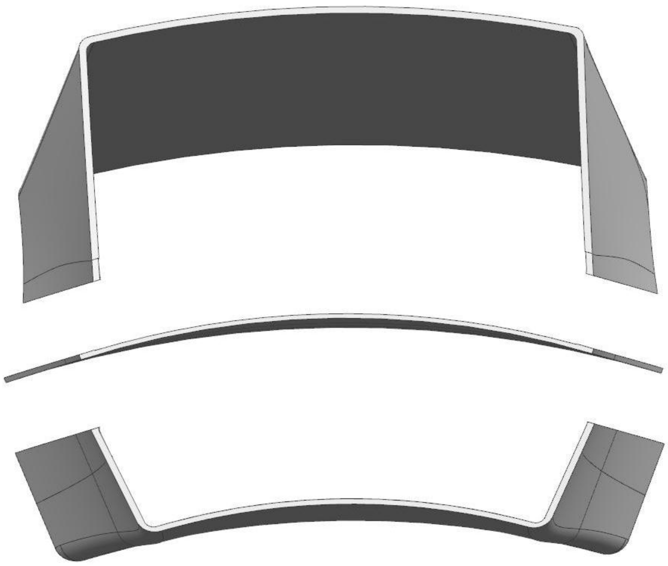


Figure 23. T-weld

7.1.2. Tie-fighter

The upper and the lower parts are pressed at the supplier like in the T-weld concept but the middle part is forged and machined, see Figure 24. The parts are then welded together at four locations. This method requires two different suppliers. This concept gives a simple welding operation but the middle part is complex and time-consuming to manufacture.

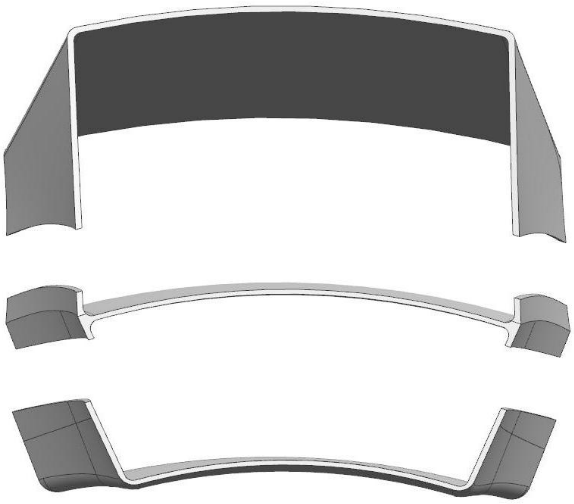


Figure 24. Tie-fighter concept

7.1.3. Crossing

The parts are pressed by the supplier but the crossing between the three parts is machined, see Figure 25. This means that a total of six welds have to be made. The Crossing concept consists of two more parts than the other concepts and requires more welding operations, it is however relative easy to manufacture.

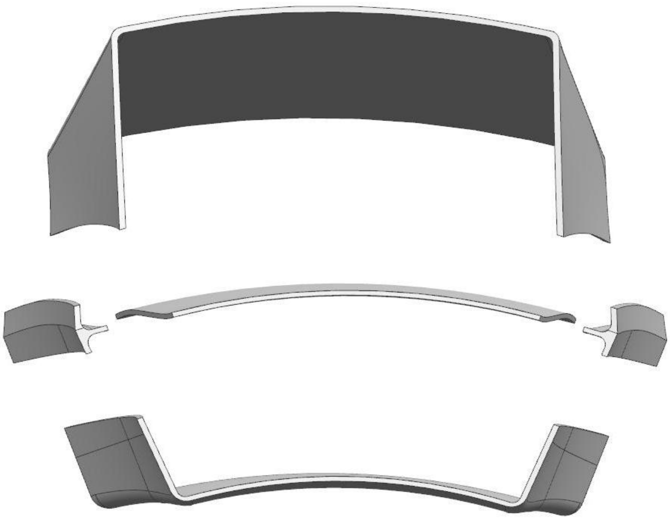


Figure 25. Crossing concept

7.1.4. LMD

The parts are warm-pressed to the same shapes as in the T-weld concept but LMD is used on the middle sheet to build it to the same shape as in the Tie-fighter concept. The welding is simplified by using LMD but the heat emitted can distort the thin sheet. The manufacturing of the concept will be time-consuming.

7.1.5. Concept selection, boxes

The box concepts are evaluated by comparing their advantages and disadvantages against each other, see Table 5.

Table 5. Concept selection for boxes

	Advantages	Disadvantages
T-weld	Few parts. No machining required. One manufacturing method. May be possible with only two joints.	T-welding must be studied.
Tie-fighter	Few parts. Easy to weld. Easy to implement radius.	Needs a forged part. Machining required.
Crossing	Three parts can be pressed. Easy to implement radius.	Six joints are required. The crossings require machining.
LMD	Three parts can be pressed. No extra parts.	HAZ from the MD. Requires subsequent machining. Time consuming.

The only disadvantage with using a T-weld is that VAC does not use T-welds in their production and therefore it has to be studied further. The T-weld has nevertheless been chosen as the preferred fabrication method since it provides a lot of beneficial properties in comparison with the other concepts, if VAC is able to verify the method it should be used.

7.2. Obtaining tight clearances between rings and boxes

The maximum joint gap between the boxes and the ring is 0,1 mm and the *profile of line* and *profile of surface* tolerances of the boxes after welding are +0,2 mm, meaning that if the aim is to get a clearance of 0,1 then the box will overlap the rings up to 0,1 mm in some places. This will give three extreme cases. These cases have a 0,1 mm joint clearance to exemplifies how the tolerances affect the clearance.

The first is the “best case scenario” when the box has not deviated anything and the clearance is 0,1 mm, see Figure 26.

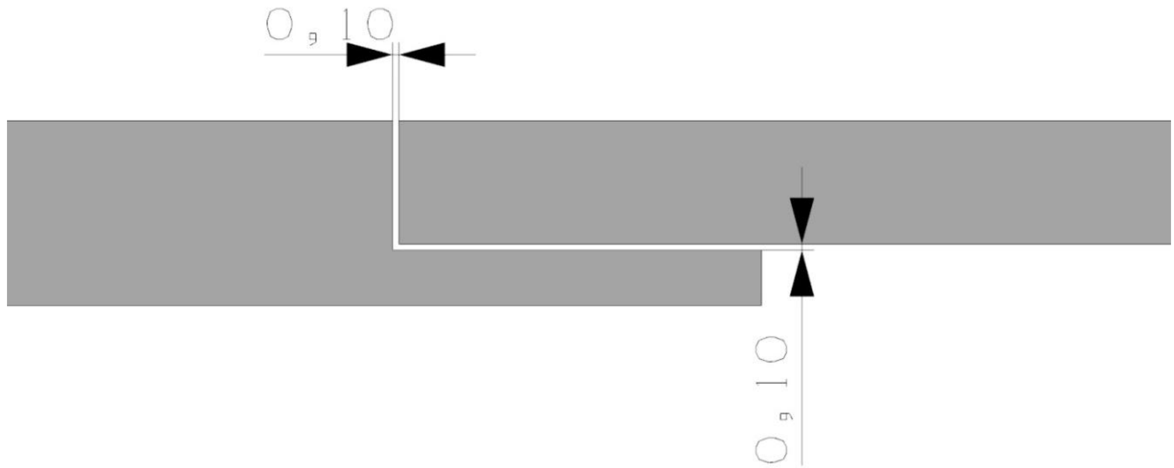


Figure 26. The joints best case scenario

The second one is when the box has varied 0,1 mm and the joint gap is 0 mm, see Figure 27.

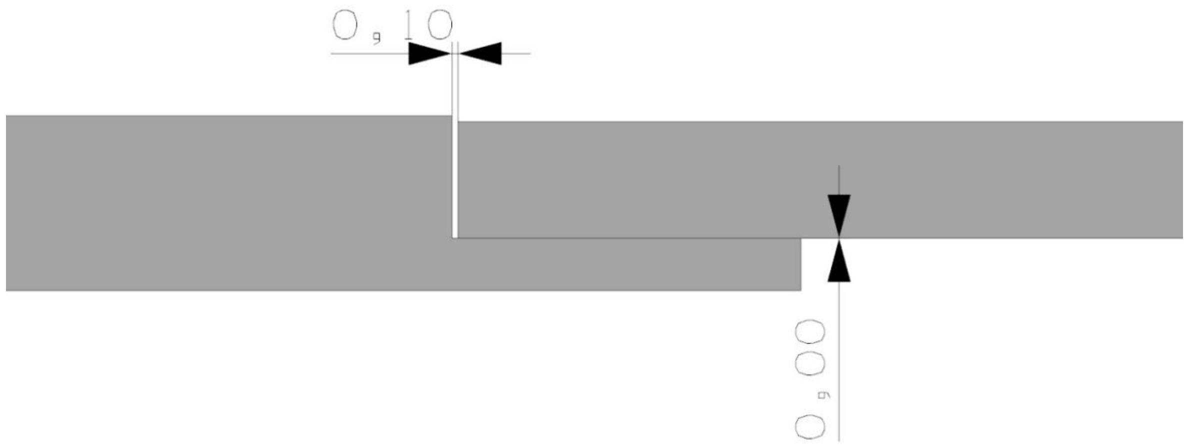


Figure 27. No gap in the joint

The last case is the “worst case scenario” when the boxes deviates 0,2 mm from the original form, giving an overlap of the ring by 0,1 mm, see Figure 28.

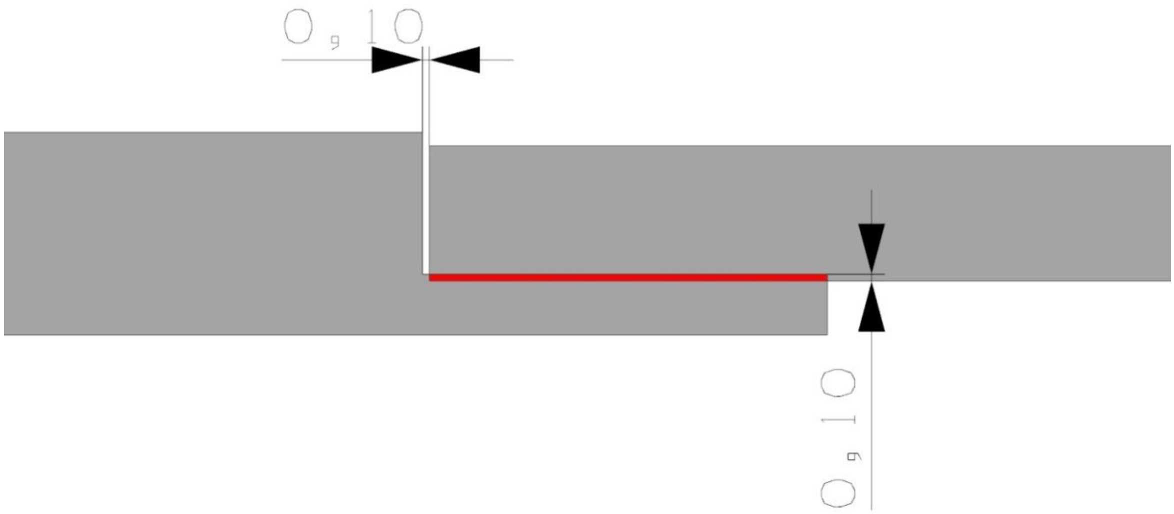


Figure 28. Worst case scenario in the joint

It is important to note that each of the three cases probably will be present on every joint between the ring and the box. It will therefore be impossible to braze the parts sufficiently without doing more machining work to position the parts properly. There are three different concepts for enabling the correct joint gaps.

7.2.1. Force

This concept needs a fixture that forces the eight boxes into the rings while the brazing is performed or a fixture which is forcing the boxes one by one and then the joints are tack-welded before the brazing. The advantage with tack-welding the parts before the brazing operation is that the fixture will be less advanced and it will not have to withstand the furnace temperature.

7.2.2. Machined boxes

The main idea is to machine the joint area of the boxes to lower the tolerances. The 6 mm joint length of the boxes will be milled to its desired shape making the joint area of the boxes look the same on every box. Notable is that the box will be higher than the ring in the “best case scenario”, this scenario occurs when the box has not deviated anything from the shape that is set as the desirable shape, see Figure 29.

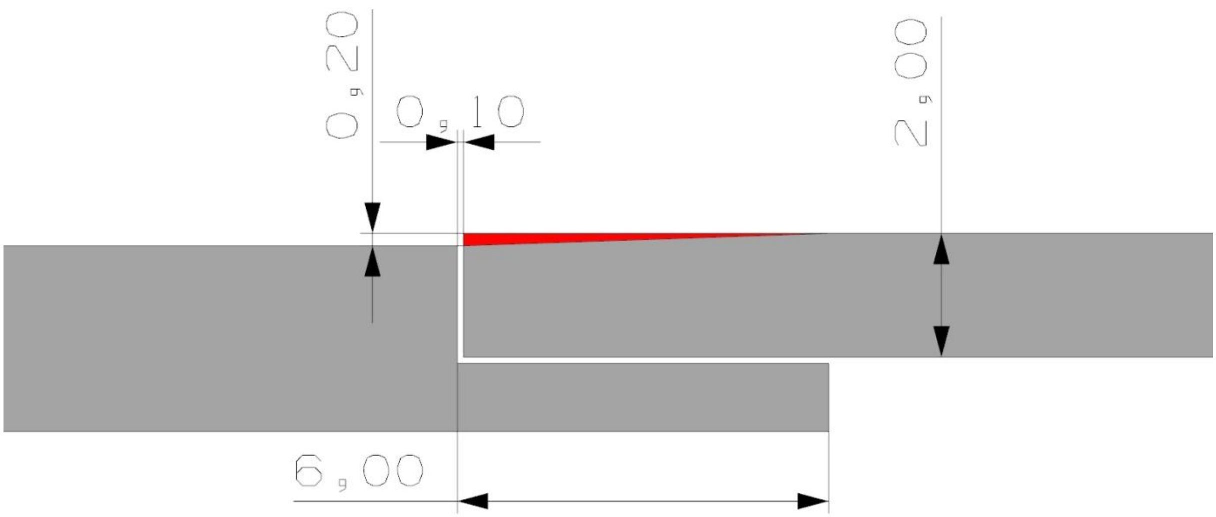


Figure 29. Best case scenario

The red area represents the material that has to be cut off. The reason for having the box higher is to ensure that all machining will be on the box instead of machining both the rings and the boxes. The geometry of the rings is fixed.

The other extreme case is the "worst case scenario" where the shape has deviated 0,2 mm, see Figure 30. The red area is the shape that will be cut from the box. The extreme cases will not be present most of the time since the shape varies along the boxes. The mill is programmed to do exactly the same operation on every box, cutting the joint on the outside of the box and the transition on the inside of the box, when the best case scenario is present then the mill will not be in contact with the work piece when trying to cut the outside of the box and vice versa in the worst case scenario.

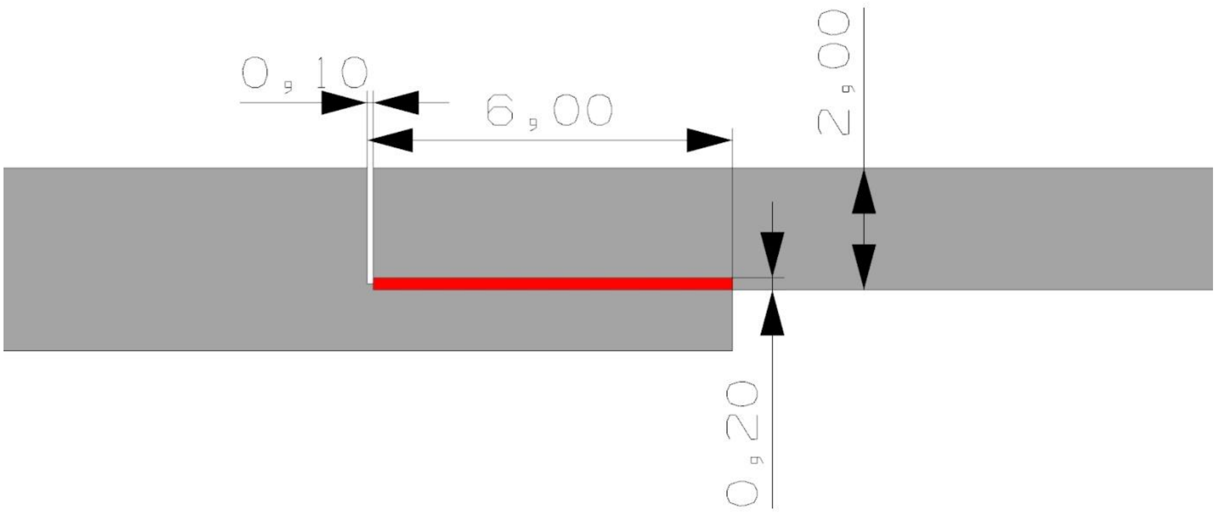


Figure 30. Worst case scenario

7.2.3. Machined rings

An option, instead of machining the boxes is to machine the rings which are sturdier than the boxes. The boxes will have to be measured with a vision system and the rings will be adjusted to fit the boxes instead of the opposite, the machining of the rings will therefore take place after the measuring of the boxes. The camera in the vision-system will measure the deviations from the required joint shape and where the box are positioned and then build a program for the milling operation. The geometry of the boxes will be unique and only fit in one place on one specific ring.

7.2.4. Concept selection, tolerances

The concepts for obtaining adequate tolerances are compared in the same way as the box concepts, see Table 6.

Table 6. Concept selection for obtaining tolerances

	Advantages	Disadvantages
Force	No machining required.	Forcing the boxes may cause stresses. Advanced fixturing. Complex to achieve.
Machined boxes	Self-fixturing. No stresses. Very good tolerances.	Machining of thin walls.
Machined rings	Self-fixturing. No stresses. Very good tolerances.	Needs vision system. No ring and box will be alike. Boxes still needs finishing.

The Force concept will be hard to accomplish and even if it is successful, it will give unnecessary stresses in the part. If the Machined rings concept is chosen; the boxes has to be tracked because they will only fit in a specific place on a specific ring. This leaves the Machined boxes concept which will require machining of thin walls, but only for a small length. The properties of this concept are basically the same as the properties for the Machined rings concept but here the boxes fit any ring.

7.3. Fixturing

One of the key aspects for successful brazing is the fixturing of the workpieces, to achieve a good braze the parts must be held with a proper gap between them, enabling the BFM to flow into the gap. The setup contains a total of ten parts (front ring, aft ring and eight boxes); this makes the fixturing complex since the parts will be brazed together in one operation. The fixturing can be done by either making a fixture that holds the parts in place in the furnace during the brazing or by making a fixture for tack-welding of the parts before putting the assembly in the furnace. A third option is to use a self-fixuring joint design.

7.3.1. Self fixturing

The chosen joint design will act as fixture, making the external fixture considerably less complex. Since the parts will be more or less self-fixturing the use of tack-welding is not needed, however it could still be used to ensure that the clearance is sufficiently tight. Figure 31 shows a simplified joint part of the ring

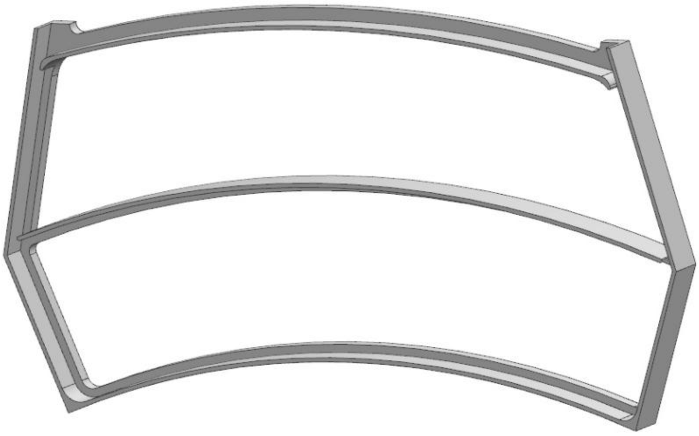


Figure 31. Simplified joint area

Figure 32 shows how the box is fitted onto the ring.

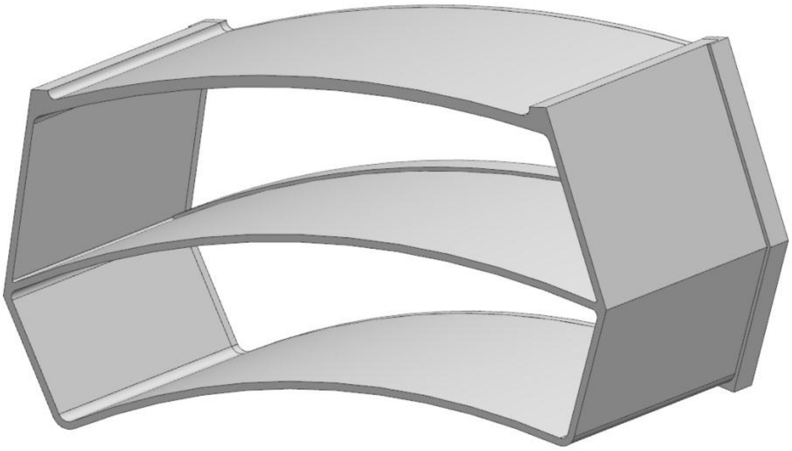


Figure 32. Box placed on the ring

7.3.2. Tack-weld

It is important to use a pure tungsten electrode when tack-welding before a brazing operation because other type of electrodes can prohibit the BFM from spreading, it is also important to use argon when welding to prevent oxidization of the steel. The tack-welding can be divided into 16 sub-operations, one for each side of the eight boxes. This means that only one sub-operation has to be considered at a time, the number of tack-welds can be adjusted to the situation, Figure 33 and Figure 34 shows where these tack-welds could be located. [1]

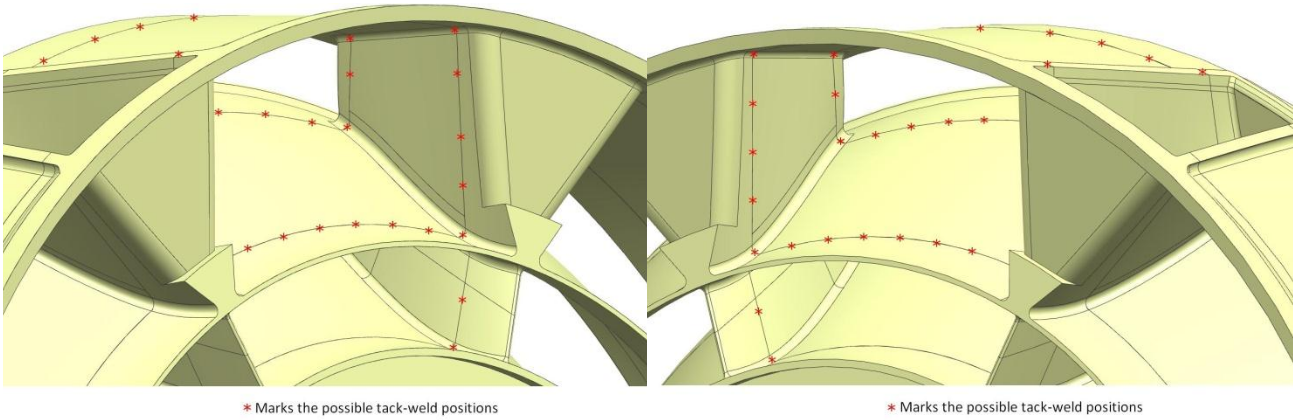


Figure 33. Positions of the tack-welds

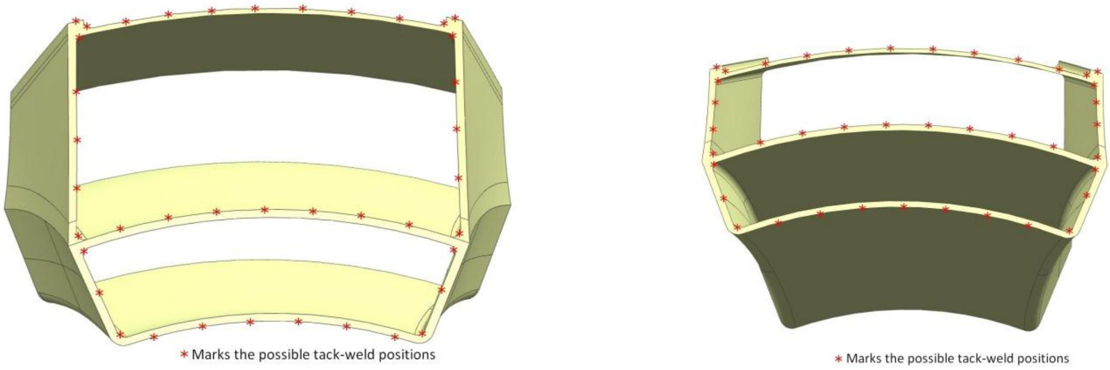


Figure 34. Position of tack-welds on both sides of the boxes

The biggest issue with tack-welding is that it will be performed in tight spaces, making access a problem. Figure 35 shows the size of two limited-access TiG welding handles compared to the size of the ICC. The left handle in Figure 35 is a Weldcraft WP-125L which is for manual welding and the right handle is ABITIG WH 400 W which is for automatic welding. The figure shows that access is a problem even with the significantly smaller manual handle. The welding operation will be time consuming with these small access margins and it will demand a skilled operator. The access problem will be aggravated by the fixturing that in some places take up the same space as the tack-welding operation. A partner to VAC has developed an adapter that allows the WP-125L manual handle to be attached on a robot. Using a robot is more time efficient and does not demand a skilled operator; it will also increase the repeatability of the process and therefore produce a more satisfying final result.

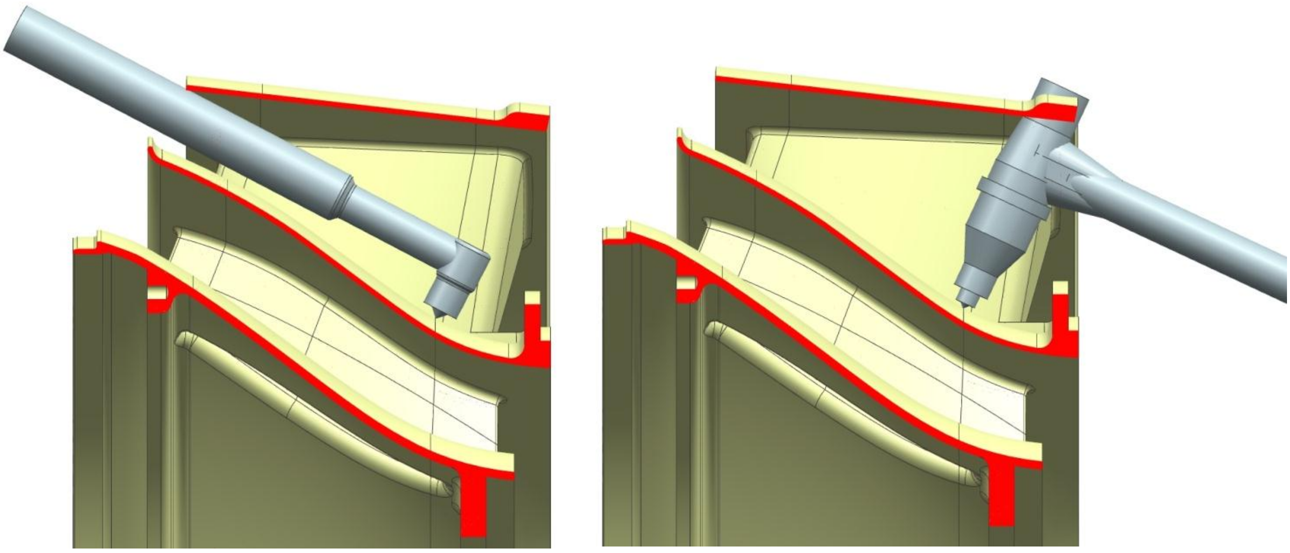


Figure 35. Access control, manual handle to the left and automatic handle to the right

7.4. Pre braze cleaning

One important factor for achieving good results when brazing is cleaning of the affected joints. All obstructions to flow, wetting and diffusion of the liquefied BFM must be removed from both joint surfaces prior to the brazing operations. Contaminations on one or both of the surfaces might result in formation of voids, encapsulated contaminations and restriction or misdirection of BFM flow, all of which reduces the mechanical properties of the joint. In some cases, including the manufacturing of the ICC, it is preferable to conduct both precleaning and cleaning of the surfaces. The parts are stored in a clean room after the precleaning and are cleaned again just before the brazing process starts. This would be the preferred method to use when manufacturing the ICC but if tack-welding is employed then the use of a cleaning agent after the tack-welding would contaminate the joint even more. This is due to the capillary forces of the tight joint that will prevent the liquid cleaning agent from leaving the joint. The cleaning of the ICCs joints will therefore only be done in one step prior to the brazing if tack-welding is used, otherwise it is preferred that the parts are cleaned in two steps. [1]

Cleaning of the surfaces can be done either mechanically or chemically but this project will only cover the more widely used chemical cleaning methods. The cleaning process usually starts with removal of grease and oil. This can be done by five different chemical cleaning methods: solvent cleaning, vapor degreasing, alkaline cleaning, emulsion cleaning or electrolytic cleaning. Applying ultrasonic vibrations to the bath can enhance all of these methods. Scale and/or oxide removal can be accomplished by the use of acid cleaning, acid pickling or slat bath pickling. [1]

It is important that all cutting fluids from the machining operations are removed. After cleaning parts can be stored up to two weeks in a clean environment before the parts are contaminated.

7.5. Furnace brazing of the ICC

Brazing may appear to be a complicated way to join the ICC but if all processes are performed correctly then getting good results from the brazing process should only be a matter of adjusting the brazing cycle correctly and then repeating the process. The BFM has the ability to climb in the opposite direction of gravity because of capillary action but designing the joints to draw BFM upwards is unnecessary if it can be avoided. Since paste will be used for the ICC, it is recommended to put the paste on the higher part of the joint gap and take advantage of the gravity for better flow. The ICC will be placed on the aft ring in the furnace because it is more planar than the front ring.

The furnace used in vacuum brazing can also be used for heat treating the steel. The furnace used for brazing the ICC must be able to obtain a vacuum level of 10^{-5} torr. It is possible to braze several ICCs at once if a larger furnace is used. A larger number of ICCs requires more heat because the heat must be distributed among a higher mass, this may cause a lower maximum heating rate.

More than one furnace is needed because the furnaces will be used for brazing, heat treatment and repair brazing. The brazing process takes over 4 hours, the heat treatment around 4 hours and the repair brazing also takes 4 hours, consequently the minimum furnace time required is about 8 hours.

7.5.1. Brazing cycle

Brazing is harder than just putting the part in the furnace and then turn up the heat, some kind of brazing cycle is often required to get the desired results. The furnace should not be heated at a rate above 15°C/min because a faster heating rate can cause spalling of the BFM paste and distortion of the assembly. The heating continues until a temperature of 25°C above the solidus temperature of the BFM is reached. The temperature is often held at some places during the cycle to even out the furnace temperature and to let the vacuum levels recover.

The brazing should be carried out at the lowest possible temperature in the brazing temperature range. Having as low temperature as possible is particularly important when brazing large gaps, thin materials and when the BFM is free-flowing. Since 17-4PH has an annealing temperature of 1038°C it is recommended to keep the temperature below this if possible. The brazing temperature should be kept until the temperature is the same everywhere in the part; this usually takes around 5-10 minutes depending of the size of the part.

The part is then slowly cooled until the furnace reaches a temperature of around 25°C below the solidus temperature; at this time argon is pumped into the furnace to force cool the part down to room temperature. The reason for not cooling the part with argon from the beginning is the risk of blowing BFM away from the joint gaps.

An example of a brazing cycle for the ICC is presented in steps below:

1) The furnace is pumped to a vacuum level of 1×10^{-5} torr.
2) The furnace is heated from room temperature to 450°C at a rate of 6°C/min.
3) Held for 10 min to allow the load to equalize to the furnace temperature.
4) Heated to 700°C at a rate of 6°C/min.
5) Held for 1 min.

6) Heated to 950°C at a rate of 6°C/min.
7) Held for 1 min.
8) Heated to 1050°C at a rate of 4°C/min.
9) Held for 10 min to allow the BFM to spread through the joint area.
10) Cooled to 950°C at a rate of 4°C/min.
11) Force cooled to room temperature by backfilling the furnace with argon.

This cycle gives a total furnace time of 228 min excluding the time for the forced cooling.

It is also possible to combine the cooling with a heat treatment for the material but the furnace must first be cooled to around 100°C and then the temperature will be raised to 593°C (1100°F) and kept for 4 hours. This heat treatment changes the condition of the material to Condition H1100. This is useful for the ICC since subsequent welding operations will be performed and the heat treatment makes the material more ductile and therefore less prone to crack propagation during the welding. Heat treatment is also used to relieve the internal stresses that occur in the material during tack-welding and brazing.

If the process can be optimized so that only a few of the ICCs must be rebrazed then it can be worth to combine the heat treatment with the brazing. If more ICCs needs rebrazing then it is not recommended because the heat treatment takes over 4 hours and there is a risk that the brazed joint is of insufficient quality, if this would be the case, several hours has been wasted on a heat treatment that must be redone after the repair brazing. Hence it can be preferable to perform the NDT before heat treating the part. [22], [23]

7.6. Non-destructive testing - NDT

If failure occurs on an ICC the consequences can be catastrophic. It is therefore of great importance that every brazed joint is tested with a NDT method. Defects that can be found by NDT includes lack of fusion at joint interfaces, cracks in joints, voids, brittle phases, poor fillets, distortion, damage to components and changed behaviour of the parent materials. NDT is used to verify that the brazing quality is sufficient. [10]

7.6.1. Visual inspection

Visual inspection is the most common inspection method; the outside of the brazed joint is inspected with or without magnification. It must be possible to inspect the joint from both sides and the method can be used to detect external voids and porosity, noncontinuous fillets, braze appearance, surface cracks, erosion, fillet size and shape. However, visual inspection cannot be used to detect internal defects like lack of fill, porosity and internal cracks. [1]

7.6.2. Proof testing

The proof testing method subjects the joint to loads exceeding the loads that acts on the component during service to verify that the component is strong enough for the application. This method does not give any information about the quality of the joint and the one-time load does not simulate the service environment hence the method is not suitable for components subjected to cyclic loads. [1]

7.6.3. Acoustic emission
Acoustic emission can be used alone or together with proof testing. When an object is exposed to external load, pressure or temperature, energy is released and sensors can pick up faults from any location in the component. Acoustic emission is good at finding voids and brittle phases. [1]

7.6.4. Radiographic inspection
Radiography uses gamma rays or X-rays to penetrate objects, shorter wavelengths gives better penetration. The material that is being inspected absorbs radiation depending on thickness and density. If there is a void or a cavity in the material then the absorbed radiation will be lesser. The variation in radiation will be recorded on a radiation sensitive film which will produce an image where defects are shown.

Radiographic inspection is useful for detecting porosity, voids and changes in material composition, with proper orientation it can also be used to find planar defects. The largest disadvantages with radiographic inspection are the hazardous radiation that the operators can be exposed to and that access to both sides of the part is needed. According to Kay; radiographic inspection should only be used when the following four criteria's are fulfilled:

- The radiographs are easy to read and interpret
- The brazed joint is larger than 2% of the metal thickness
- It is possible to take radiographs of all critical brazed surfaces
- Radiographic inspection does not affect other processes in the brazing like BFM selection. [24], [25]

7.6.5. Ultrasonic inspection
In ultrasonic inspection a sound wave is emitted from a transducer and the reflections in form of echoes is returned and measured. The returned echoes are then displayed on an oscilloscope or a facsimile created by a recording pen. Ultrasonic inspection is a comparative method; hence a reference is needed to ease the interpretation of the results. It is possible to detect both surface and internal defects with this method. Voids, cracks, lack of bonding, contamination and brittle phases can be detected with this method. Ultrasonic inspection is a cheap method and only one accessible side is needed for testing. This method is considered as one of the best methods for evaluation of joint quality. [26]

7.6.6. Penetrant inspection
Liquid penetrants can be used to detect imperfections that are open to the surface. When brazed joints have been machined the use of penetrants can detect cracks and surface porosity. The method can also be used to observe incomplete flow and partial fillets. Penetrant inspection may be risky to use if subsequent repairs will be made because it can be difficult or even impossible to remove the penetrants completely. [1]

7.6.7. Chosen testing method
A table that describes what the different methods are capable of was compiled to aid the selection of testing method/methods. Table 7 below describes the testing methods characteristics.

Table 7. Testing method characteristics

	Voids	Joint cracks	Embrittling phases	Poor fillets	Damaged components
Visual inspection	N	N	N	Y	Y
Proof testing	N	N	N	N	N
Acoustic emission	Y	N	Y	N	N
Radiographic inspection	Y	Y	Y	N	Y
Ultrasonic inspection	Y	Y	Y	N	Y
Penetrant inspection	N	N	N	Y	Y

The table shows that proof testing does not give any information on the joint characteristics; instead it shows that the joint can survive a one-time load. Radiographic inspection and ultrasonic inspection can be used to find voids, joint cracks, embrittling phases and damaged components. Since these methods can detect a wide variety of defects one of them should be used together with either visual inspection or penetrant inspection as a complement because of their ability to detect poor fillets.

VAC currently uses ultrasonic inspection, penetrant inspection, visual inspection and sometimes radiographic inspection to verify that the joints are of sufficient quality. Penetrant inspection is not suitable for this application because there is a risk that the material will be contaminated, prohibiting repairing of improper joints and thus forcing the part to be discarded which gives a large cost. Ultrasonic inspection is one of the most common inspection methods on VAC and exhibits several advantages compared to radiographic inspection where two of the main advantages are the usage cost and the lack of ionizing radiation. Visual inspection together with ultrasonic inspection is hence chosen as the desired NDT-methods.

7.7. Repairing

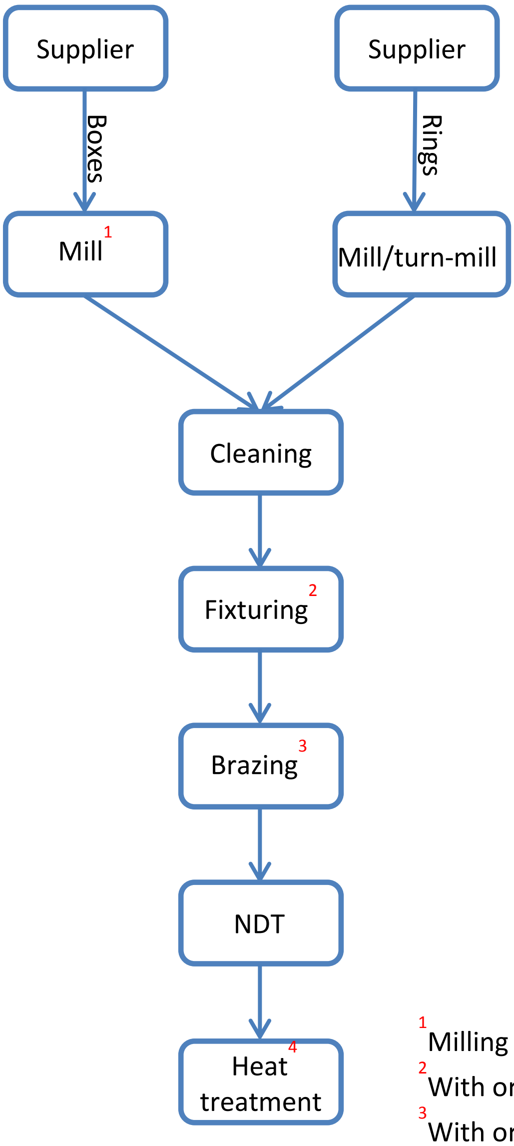
Repairing of the work piece might be necessary if any of the NDT methods reveals a critical quality defect of the brazed joint. It can be preferable to reject a product rather than repairing it if the product is inexpensive and the production rate is high. The ICC is a very expensive and low production rate product and should therefore only be rejected if no other options are available.

NDT methods can reveal voids, cracks, embrittling phases, poor fillets and damaged components. All of these quality defects can be repaired by simply putting the assembly through the same brazing cycle again. Additional BFM needs to be added to the joint in the case of poor fillet of the brazed joint. Even though a rebraze can repair the critical quality defects of a joint, it can also produce new ones. It can therefore be necessary to rebraze more than one time to achieve acceptable results. There is also another downside to rebrazing, the stainless steel will lose some of its strength with every brazing cycle since the furnace brazing temperature exceeds the annealing temperature of 17-4PH.

A limit for the maximum allowance of voids, cracks and embrittling phases must be specified. Rebrazing must be performed if the limit of any of these parameters is exceeded.

7.8. Process map

A process map was made to get a better understanding of the manufacturing processes and to show the work flow, Figure 36.



[1] Milling can be performed at suppliers
[2] With or without tack-welding
[3] With or without heat treatment
[4] Integrated in brazing if numbers of rebrazes are low

Figure 36. Process map

8. Technology Readiness Level

The definition of TRL according to NASA:

Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and consistent comparison of maturity between different types of technology.

NASA also describes what the most useful model must include:

(a) 'basic' research in new technologies and concepts (targeting identified goals, but not necessary specific systems), (b) focused technology development addressing specific technologies for one or more potential identified applications, (c) technology development and demonstration for each specific application before the beginning of full system development of that application, (d) system development (through first unit fabrication), and (e) system 'launch' and operations. [27]

NASA describes the nine TRLs:

TRL 1	*Basic principles observed and reported*
TRL 2	*Technology concept and/or application formulated*
TRL 3	*Analytical and experimental critical function and/or characteristic proof-of concept*
TRL 4	*Component and/or breadboard validation in laboratory environment*
TRL 5	*Component and/or breadboard validation in relevant environment*
TRL 6	*System/subsystem model or prototype demonstration in a relevant environment (ground or space)*
TRL 7	*System prototype demonstration in a space environment*
TRL 8	*Actual system completed and "flight qualified" through test and demonstration (ground or space)*
TRL 9	*Actual system "flight proven" through successful mission operations*

VAC has adopted this method and compiled a checklist document to follow the progress of each technology. This checklist only includes the first six TRLs.

Brazing has a low TRL at VAC, the brazing work that are performed are all assignments with well-defined parameters. VAC does not design parts for brazing, hence the low TRL and they would have to increase brazing to TRL 6 if they were to start producing the spider concept investigated in this thesis work. VACs checklist document has been used during the progress of the thesis work to check if any of the TRLs have been fulfilled.

TRL 3 can be achieved fairly easy by the use of this thesis work. Most of the questions from the checklist document can be answered, with the exception of the cost and risk questions which have to be further investigated.

Many of the criteria for TRL 6 have already been fulfilled by VAC since brazing is already used in the production. VAC has the required knowledge and suppliers to produce brazed products. The following points needs to be accomplished in order to achieve TRL 6:

- Further investigate other heating methods
- Investigate which type of products brazing can be applied on
- Further investigate the cost benefits/risk with brazing
- Investigate what risks are involved with using this technology
- Roughly made plan for increasing to TRL 7-8

9. Time/Cost analysis

A cost calculation would give results that could be used in a comparison with other concepts, but a correctly performed cost calculation would have to involve everything from material cost to operational cost for every process, all of which is very hard to find correct numbers for. Hence was a time comparison study performed instead, Table 8. The time study can only be used as an evaluation between different concepts. A full cost analysis will have to be performed by VAC with the same method and parameters as in the cost analysis of VACs other concepts.

Table 8. Time comparison between different concepts

Joint design	
	Manufacturing time ranking
Concept#1	2
Concept#2	1
Concept#3	3
Box manufacturing	
	Manufacturing time ranking
T-weld	1
Tie-fighter	4
Crossing	2
Metal deposition	3
Obtaining tight tolerances	
	Manufacturing time ranking
Force	1
Machined boxes	2
Machined rings	3
Fixturing	
	Manufacturing time ranking
Self fixturing	1
Tack-welding	2

10. Conclusions

The aim with the project was to investigate if it is possible to braze the spider concept of the ICC. The brazing in itself is not the problem instead it is the tight tolerances needed and the large joint area in this application. This led to the conclusion that if the parts in the ICC are manufactured in the correct way with tight tolerances then the brazing will not be a problem. Since the rings are machined from forged steel their tolerances will be sufficient enough but the boxes that are pressed and then welded was a problem because the surface line tolerances given by the supplier were as high as 0,8 mm. The supplier later stated that it should be possible to lower the tolerances to 0,2 mm and to control the variation to the positive side. This enabled the possibility to machine the boxes joint area to its final shape and thereby obtaining the needed tolerances.

The design of the joint provides the possibility to have a simple fixturing. A fixture that keeps the rings and boxes in place in the furnace can be used; another option is to tack-weld the parts before brazing. The tack-welding should be made with a TiG-weld with a pure tungsten electrode and argon should be used to keep the joint clean.

Höganäs Ni-613 should be used as BFM because of its flow and wetting capabilities. The more traditionally used BNi-2 exhibits better strength but has inferior flow and wetting and if Ni-613 is able to provide the needed strength then it should be used.

The TRL should be increased to make brazing a usable method. The suggestions in the TRL chapter can aid the work for enhancing the TRL.

11. Discussion

The discussion is divided into subchapters to make it easier for the reader to get an overall picture of the project work.

11.1. Joint design

Concept #2 was chosen as the preferable joint design for the spider concept but that was on the ground that the box did not need any machining. It turned out to be impossible to obtain the desired tight tolerances between the box and the ring without performing some kind of machining operation. This means that Concept #1 has no disadvantage compared to Concept #2 and should due to its lower weight be the preferable concept. Concept #1 should in theory give the same result as Concept #2 in a tensile test. Concept #1 and Concept #2 utilizes the same self-fixturing. The joint clearance should be as small as possible, the production concept will have good precision thus obtaining the correct joint clearance will be easy.

11.2. BFM

The evaluation matrix that was used to choose BFM needed a lot of information about each BFM. Many of the parameters were found in form of numbers and were easily adapted into the matrix, other parameters were not as easily adapted and were translated into number in a matter that the authors seemed fit.

The information about each BFMs thermal expansion coefficient has been near impossible to find since most BFM manufacturers do not specify that information. Nickel based BFMs have a nickel count of over 80% and should therefore have a thermal expansion coefficient close to that of pure nickel. Nickel and 17-4PH has a thermal expansion coefficient that is close to each other and should therefore produce very low residual stresses when brazed together.

11.3. Production

One of the goals of this project was to present an automated fabrication line. This thesis work has been limited to examine the processes before, during and after the furnace brazing. These processes include machining of the boxes and the rings, cleaning, fixturing, brazing, NDT and heat treatment. Of these processes, only machining of the boxes and, in the case of tack-welding, fixturing is suitable for automation. Hence has no automated line proposal been presented in this thesis work.

Repairing should in theory never have to be performed on a brazed part. Defects in a brazed part should be considered a result of incorrect brazing parameters, inadequate cleaning or incorrect joint clearance. Much time and effort should be put into optimizing these parameters, ensuring that as few repairs as possible have to be performed.

It should be investigated if the 0 mm joint clearance works and gives the desired characteristics. This will be the best clearance to use if it is possible since it will simplify the fixturing. The filler metals and the 0 mm joint clearances were supposed to be investigated with a tensile test, unfortunately the test failed so it would be advised that a test is made to verify that the 0 mm clearance is feasible.

11.4. Tensile test

The tensile test was not a complete failure even though the actual tensile test was never performed. The visual inspection suggested that the 0 mm clearance will be feasible, but further investigation has to be made to completely verify the method. A comparative analysis between the different clearances tensile strength should also be conducted. Suggestion for future testing was developed from the lessons learned from the failed brazing.

11.5. NDT

Which NDT method to use can be further investigated by checking if there is access to the joints for the NDT equipment. NDT is common in the aero industry and VAC has knowledge about NDT on welded components. Performing NDT on brazed components should not be much different from doing it on welded components thus an extensive investigation of NDT were unnecessary.

11.6. Pre-braze cleaning

It is important to clean the work-pieces thoroughly before brazing. VAC are experienced with components that need cleaning and have knowledge on how a pre-braze cleaning should be performed; hence a deeper analysis of cleaning methods was redundant

11.7. Time/cost analysis

The time/cost analysis performed in the thesis is only usable to evaluate the concepts based on time. A more extensive analysis should be made by VAC who can better estimate the costs for the processes and compare it with other concepts.

11.8. Unfulfilled deliverables

One of the initial goals was to conduct a geometry assurance analysis together with VAC, this analysis turned out to be unnecessary due to the self-fixturing design of the joint. Visualization of the process was another part of this project that was not included in the thesis report due to almost no automated processes and very long operation times for every process.

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13. Appendix

Title	Number of pages
1: Brazing Filler Metals	2
2: Tensile test piece dimensions	1
3: Mission statement	2
4: Microscopic analysis	7

Table 9. Silver BFMs

Type	Composition %									Solidus temp [°C]	Liquidus temp [°C]	Brazing temp range [°C]
	Ag	Cu	Zn	Cd	Ni	Sn	Li	Mn	Other			
BAg-1	44-46	14-16	14-18	23-25	…	…	…	…	0,15	607	618	618-760
BAg-1a	49-51	14,5-16.5	14,5-18,5	17-19	…	…	…	…	0,15	627	635	635-760
BAg-2	34-36	25-27	19-23	17-19	…	…	…	…	0,15	607	701	701-843
BAg-2a	29-31	26-28	21-25	19-21	…	…	…	…	0,15	607	710	710-843
BAg-3	49-51	14,5-16,5	13,5-17,5	15-17	2,5-3,5	…	…	…	0,15	632	688	688-816
BAg-4	39-41	29-31	26-30	…	1,5-2,5	…	…	…	0,15	671	779	779-899
BAg-5	44-46	29-31	23-27	…	…	…	…	…	0,15	677	743	743-843
BAg-6	49-51	33-35	14-18	…	…	…	…	…	0,15	688	774	774-871
BAg-7	55-57	21-23	15-19	…	…	4,5-5,5	…	…	0,15	618	651	651-760
BAg-8	71-73	bal	…	…	…	…	…	…	0,15	779	779	779-899
BAg-8a	71-73	bal	…	…	…	…	0,25-0,5	…	0,15	766	766	766-871
BAg-9	64-66	19-21	13-17	…	…	…	…	…	0,15	671	713	713-843
BAg-10	69-71	19-21	8-12	…	…	…	…	…	0,15	690	738	738-843
BAg-13	53-55	bal	4-6	…	0,5-1,5	…	…	…	0,15	713	857	857-969
BAg-13a	55-57	bal	…	…	1,5-2,5	…	…	…	0,15	771	893	871-982
BAg-18	59-61	bal	…	…	…	9,5-10,5	…	…	0,15	601	713	713-843
BAg-19	92-93	bal	…	…	…	…	0,15-0,3	…	0,15	760	885	877-982
BAg-20	29-31	37-39	30-34	…	…	…	…	…	0,15	677	766	766-871
BAg-21	62-64	27,5-29,5	…	…	2-3	5-7	…	…	0,15	690	801	801-899
BAg-22	48-50	15-17	21-25	…	4-5	…	…	7,0-8,0	0,15	682	699	699-830
BAg-23	84-86	…	…	…	…	…	…	bal	0,15	960	971	971-1038
BAg-24	49-51	19-21	26-30	…	1,5-2,5	…	…	…	0,15	660	707	707-790
BAg-25	19-21	39-41	33-37	…	…	…	…	4,5-5,5	0,15	738	790	790-846
BAg-26	24-26	37-39	31-35	…	1,5-2,5	…	…	1,5-2,5	0,15	707	801	801-871
BAg-27	24-26	34-36	24,5-28,5	12,5-14,5	…	…	…	…	0,15	607	746	746-857
BAg-28	39-41	29-31	26-30	…	…	1,5-2,5	…	…	0,15	649	710	710-843

Table 10. Nickel BFMs

Type	Composition %												Solidus temp [°C]	Liquidus temp [°C]	Temp. range [°C]
	Cr	B	Si	Fe	C	P	S	Mn	Cu	Zr	Ni	Others			
BNi-1	13-15	2,8-3,5	4-5	4-5	0,6-0,9	0,02	0,02	…	…	0,05	bal	0,5	977	1038	1066-1204
BNi-1a	13-15	2,8-3,5	4-5	4-5	0,06	0,02	0,02	…	…	0,05	bal	0,5	977	1077	1077-1204
BNi-2	6-8	2,8-3,5	4-5	2,5-3,5	0,06	0,02	0,02	…	…	0,05	bal	0,5	971	999	1010-1177
BNi-3	…	2,8-3,5	4-5	0,5	0,06	0,02	0,02	…	…	0,05	bal	0,5	982	1038	1010-1177
BNi-4	…	1,5-2,2	3-4	1,5	0,06	0,02	0,02	…	…	0,05	bal	0,5	982	1066	1010-1177
BNi-5	18,5-19,5	0,03	9,8-10,5	…	0,1	0,02	0,02	…	…	0,05	bal	0,5	1080	1135	1149-1204
BNi-6	…	…	…	…	0,1	10-12	0,02	…	…	0,05	bal	0,5	877	877	927-1093
BNi-7	13-15	0,01	0,1	0,2	0,08	9,8-10,5	0,02	0,04	…	0,05	bal	0,5	888	888	927-1093
BNi-8	…	…	6-8	…		0,02	0,02	21,5-24,5	4-5	0,05	bal	0,05	982	1010	1010-1093

Table 11. Gold BFMs

Type	Composition %					Solidus temp [°C]	Liquidus temp [°C]	Temp. range [°C]
	Au	Cu	Pd	Ni	Others			
BAu-1	37-38	bal	…	…	0,15	990	1016	1016-1093
BAu-2	79,5-80,5	bal	…	…	0,15	890	890	890-1010
BAu-3	34,5-35,5	bal	…	2,5-3,5	0,15	974	1030	1030-1090
BAu-4	81,5-82,5	…	…	bal	0,15	949	949	949-1004
BAu-5	29,5-30,5	…	33,5-34,5	35,5-36,5	0,15	1135	1166	1166-1232
BAu-6	69,5-70,5	…	7,5-8,5	21,5-22,5	0,15	1007	1046	1046-1121

Table 12. Other BFMs

Type	Composition %										Solidus temp [°C]	Liquidus temp [°C]	Brazing temp range [°C]
	Pd	Cr	B	Ni	Cu	P	Si	Mn	Fe	Co			
PalNicro-30	10,5	30	2,4	bal	…	…	…	…	…	…	941	977	1020-1050
Hi-Temp 095	…	…	…	9,5	52,5	…	…	bal	…	…	880	925	925-1095
Hi-Temp 870	…	…	…	…	87	…	…	10	…	3	960	1030	1010-1093
BrazeLet Ni613	…	29	…	bal	…	6	4	…	…	…			~1080
BrazeLet F300	…	32	…	20	10	7	5	5	bal	…			~1120

Appendix 2. Tensile test piece dimensions

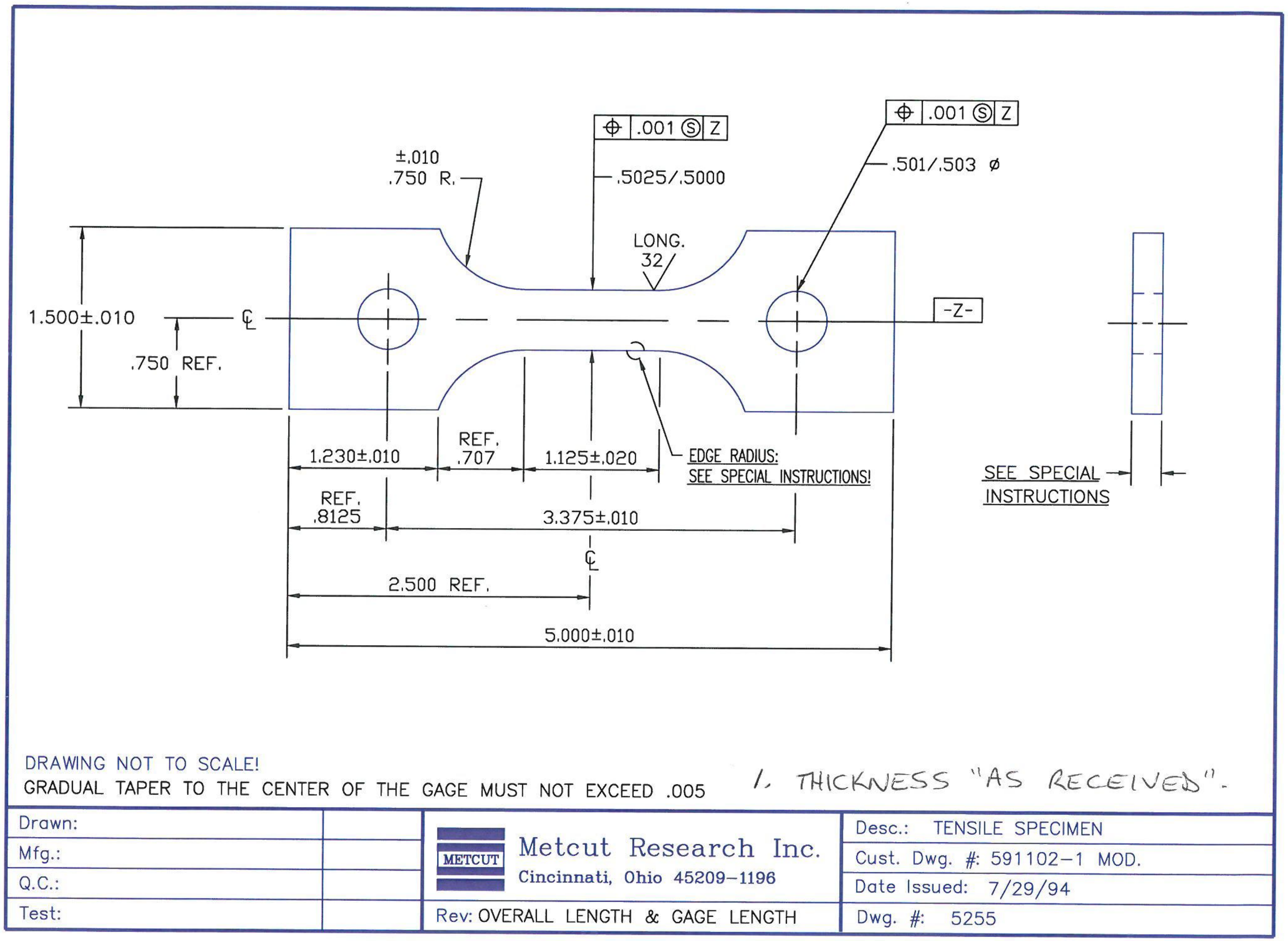

Figure 37. Tensile test piece dimensions

Thesis Work – Definition 20p

Producability of an Advanced Intermediate Compressor Case

Background:
Volvo Aero has developed ICC's (Intermediate Compressor Case) for a numerous big and medium aircraft engines. During the course of the development work the focus on "green" solutions has increased e.g. to lower the fuel burn, but also the focus on cost has increased incredible, due to the amazing competition.

Compressor structures in aircraft engines are generally made in Titanium, due to the density/weight ratio. Titanium is expensive and casting founders are few, which results in high cost. Trend of today is to fabricate instead of casting and next step is new materials. Modern Stainless Steels have great potential to challenge Titanium with good density/weight ratio, very high performance and also high temperature resistance.

Objective:
The aim of the work focuses on how to produce a new concept for an ICC, in Stainless Steel, that is possible to fabricate to a 30% lower cost, compared to a cast concept in Ti. The concept is designed starting from warm formed sheet metal and two forged "rings" that is brazed together. Important part in the project is to understand the warm forming process and also how to braze all parts together. Use of geometry assurance to minimize the end tolerances is a key to success. Another success factor is to develop the process for brazing in Stainless Steel, in a high volume production. Cooperation with suppliers is needed.

Deliverables:

- Proposal for an automation fabrication line for the ICC concept.
- Visualization of the process, if possible.
- Geometry assurance report and proposals.
- Cost and investment analysis.
- Evaluation of the brazing method and material tests for verification.
- Thesis Report (in English)

The thesis work will begin with documentary research, project planning and training in Geometry Assurance and other tools necessary for the work. The thesis work is aimed for two persons.

Recommended academic bearing:
M.sc. Mechanical Engineering. Interest of production aspects is favourable.

For further information about the thesis work, contact:
Lars-Olof Hellgren. Tfn: 0520-98729 or e-mail: lars-olof.hellgren@volvo.com
Dep: 9641, Cold Structures
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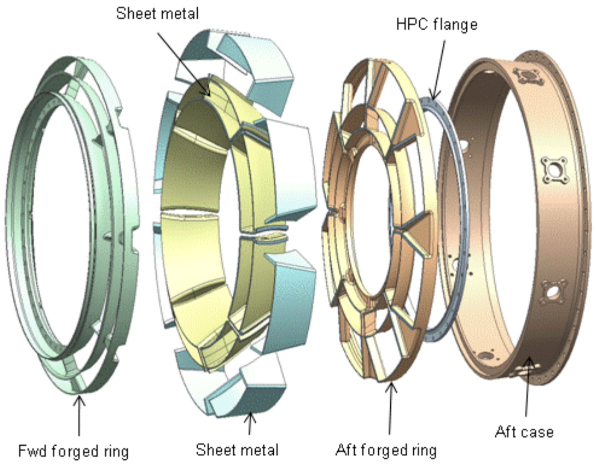
Dep: 9641, Cold Structures
Volvo Aero Corporation, Trollhättan.

This particular thesis work is not part of the military department at Volvo Aero and is open for other nationalities. Selected students can be subject to a security control by the Swedish security police. More information about the conditions for thesis works can be found on Volvo Groups homepage: http://www.volvo.com/group/global/en-gb/career/studentopportunities/conditionsthesiswork.htm

Last day to apply for this thesis work is the 24:th of June 2010.
Day of beginning is set by a mutual agreement.

Concept <u>SPIDER</u>



Risks:

— Soldering in oven (low TRL)

— Small joint tolerances required (≤ 0.1 mm)

— Difficulties applying the solder

— If welding is chosen as joining method, the welding shrinkage will be hard to handle as lots of parts will be joined in the same setup

+	—
Soldering ➔ low heating	Soldering in oven – low TRL
Sheet forming used	Joint tolerances (≤ 0,1mm)
Less machining required	

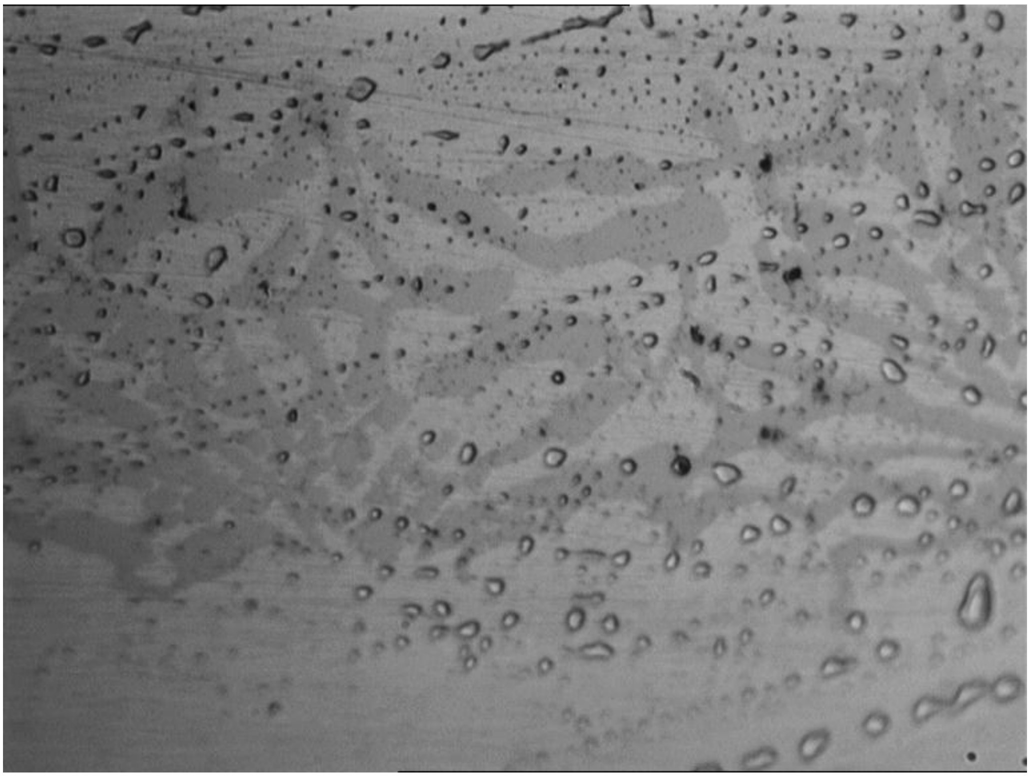


Figure 38. Ni-613 with 0,05 mm clearance. Highly magnified. Free from from voids

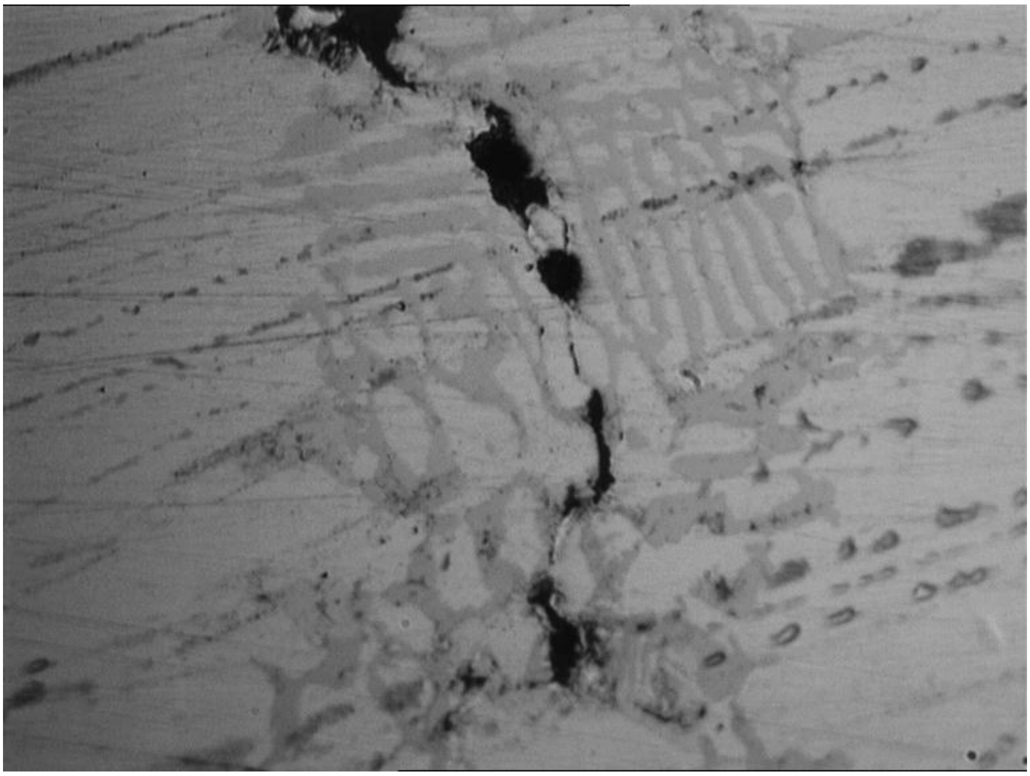


Figure 39. Ni-613 with 0,05 mm clearance. Highly magnified. Voids due to lack of BFM

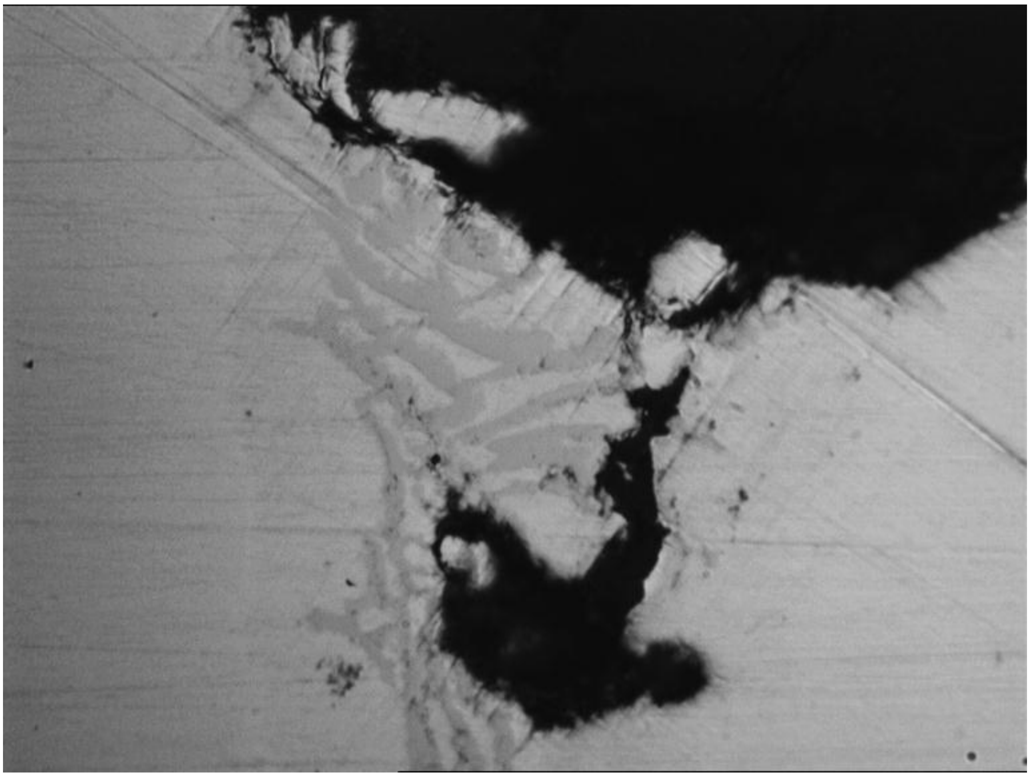


Figure 40. Ni-613 with 0,05 mm clearance. Highly magnified. Joint end.

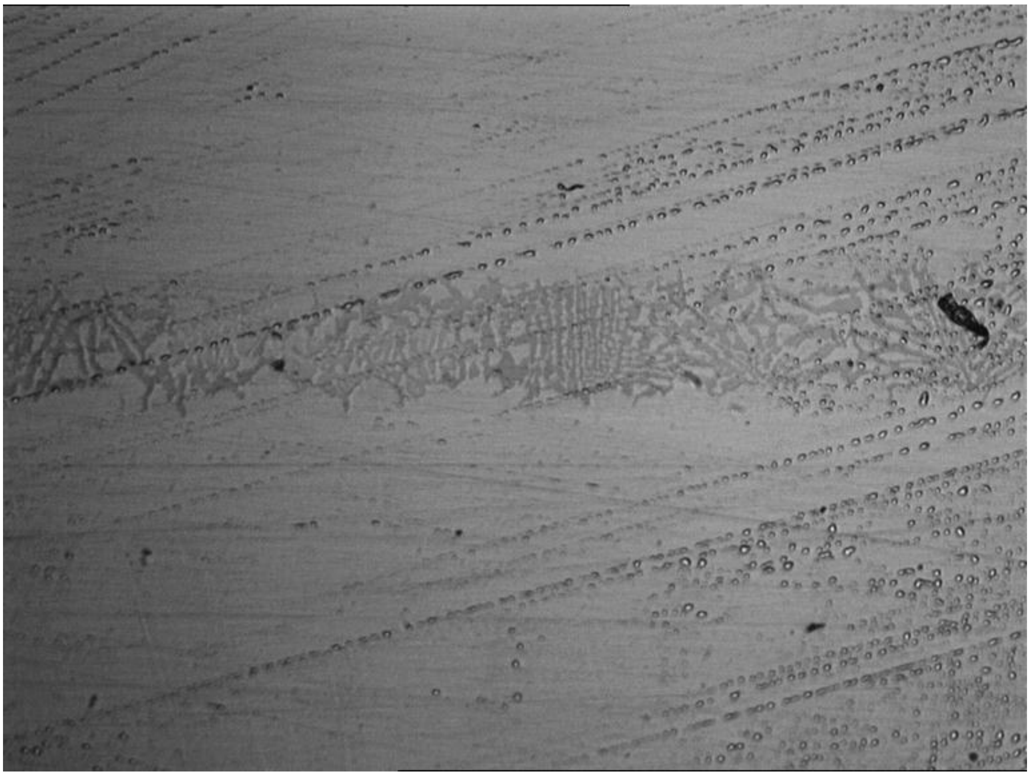


Figure 41. Ni-613 with 0,05 mm clearance. One void but free from other irregularities

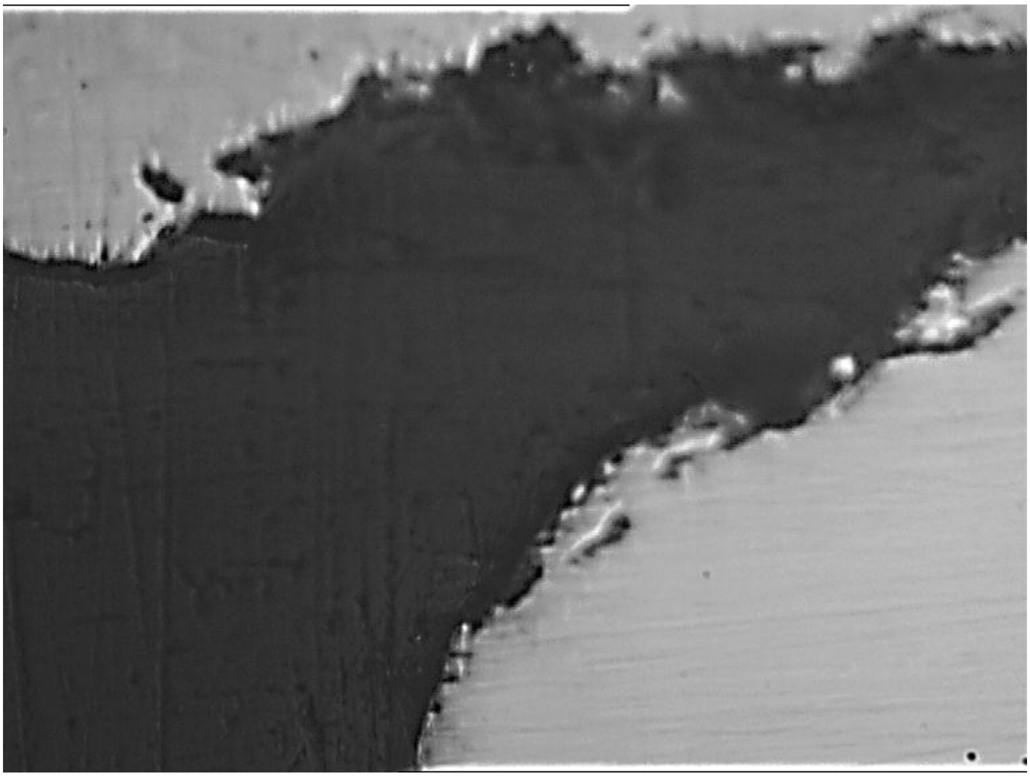


Figure 42. Ni-613 with 0 mm clearance. Highly magnified. Joint start.

Figure 43. Ni-613 with 0 mm joint clearance. Highly magnified. Lack of BFM.

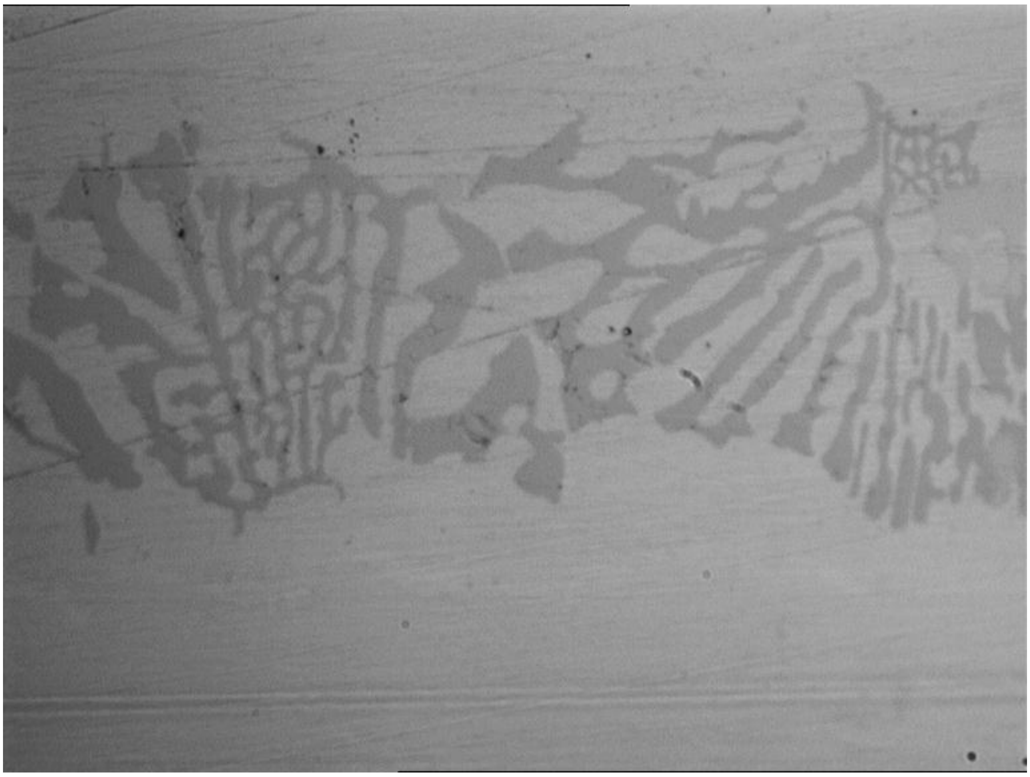


Figure 44. Ni-613 with 0 mm joint clearance. Highly magnified.

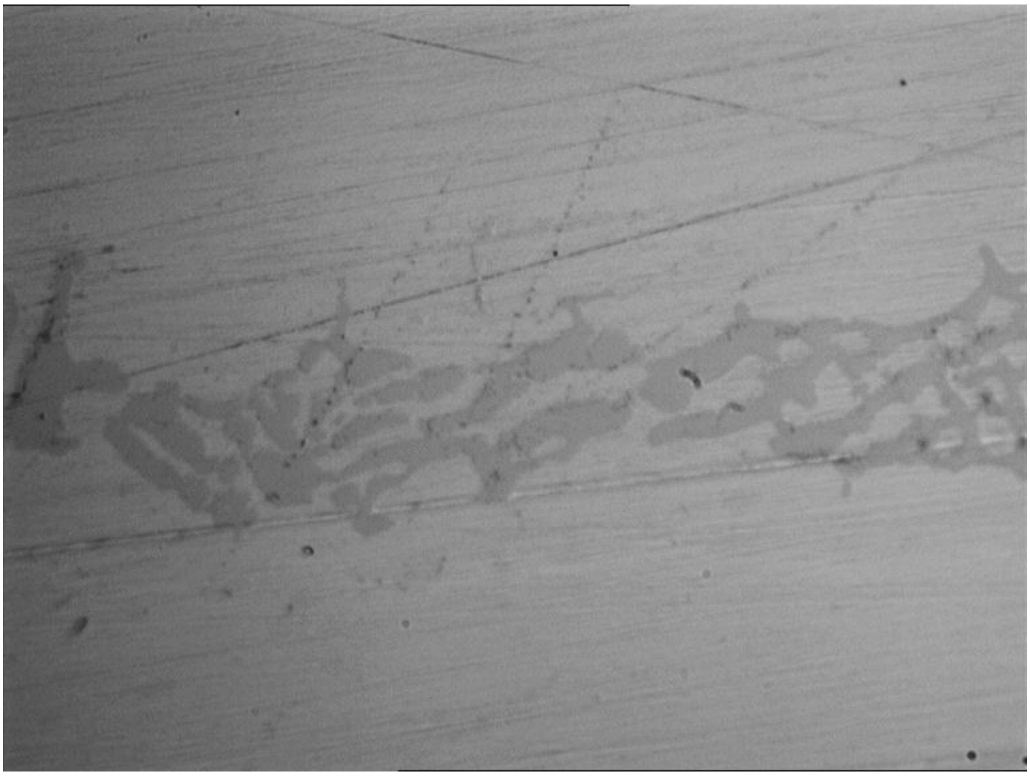


Figure 45. Ni-613 with 0 mm joint clearance. Highly magnified.

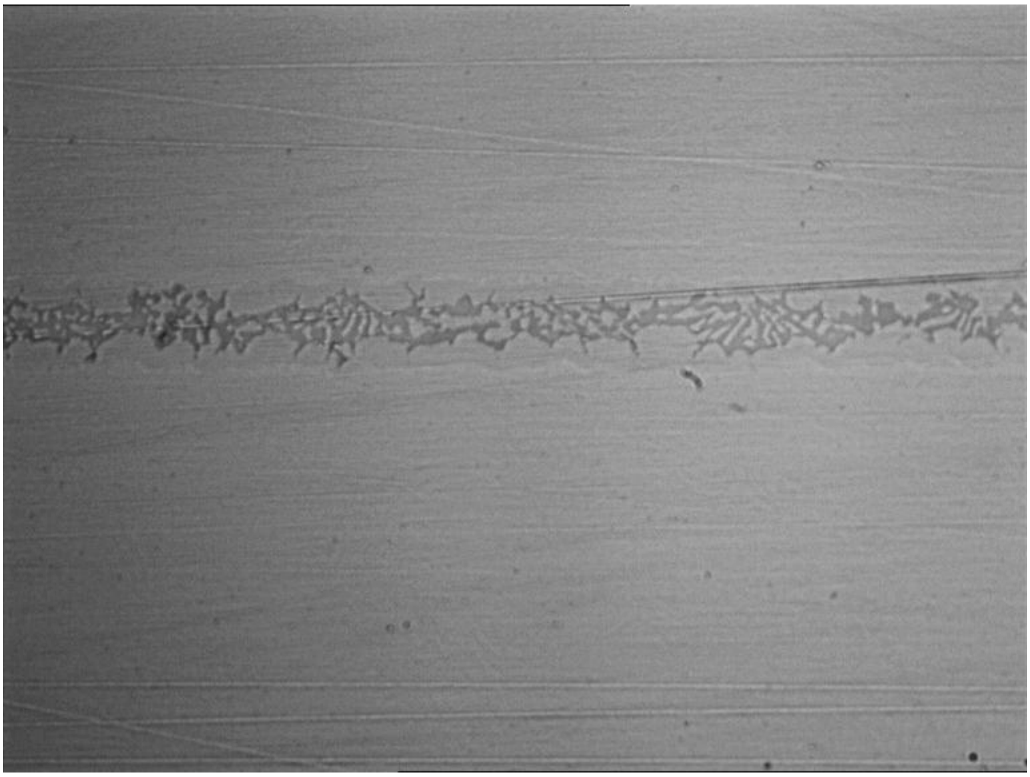


Figure 46. Ni-613 with 0 mm joint clearance.

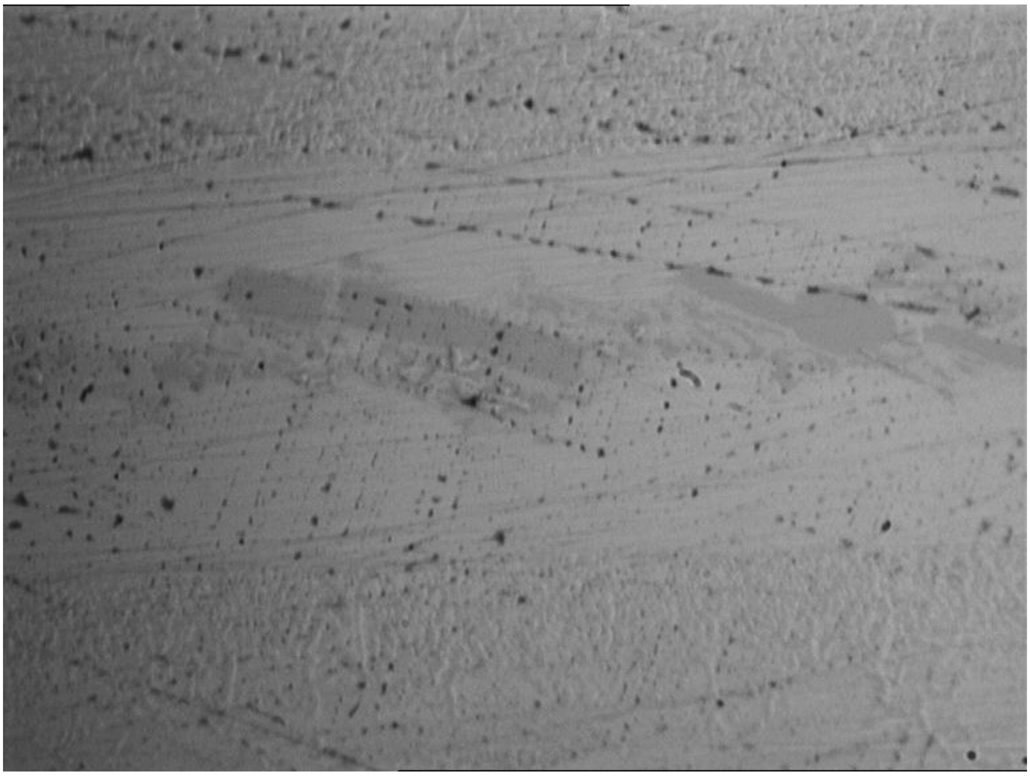


Figure 47. BNi-2 with 0 mm joint clearance. Highly magnified.

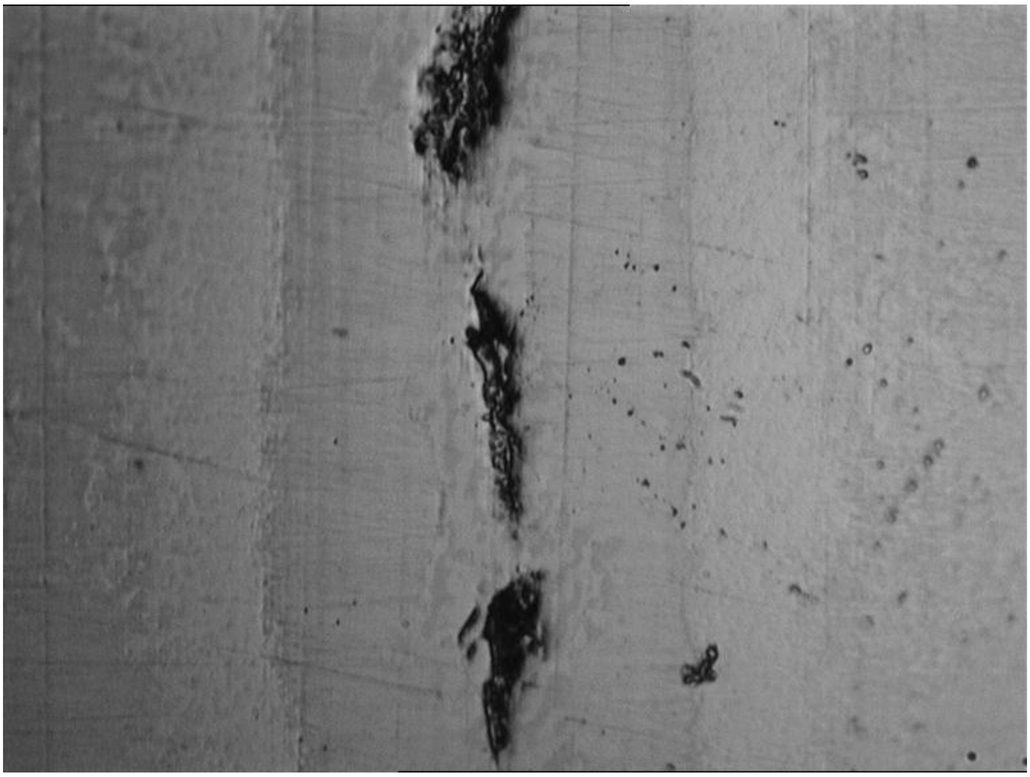


Figure 48. BNi-2 with 0 mm joint clearance. Highly magnified. Voids due to lack of BFM.

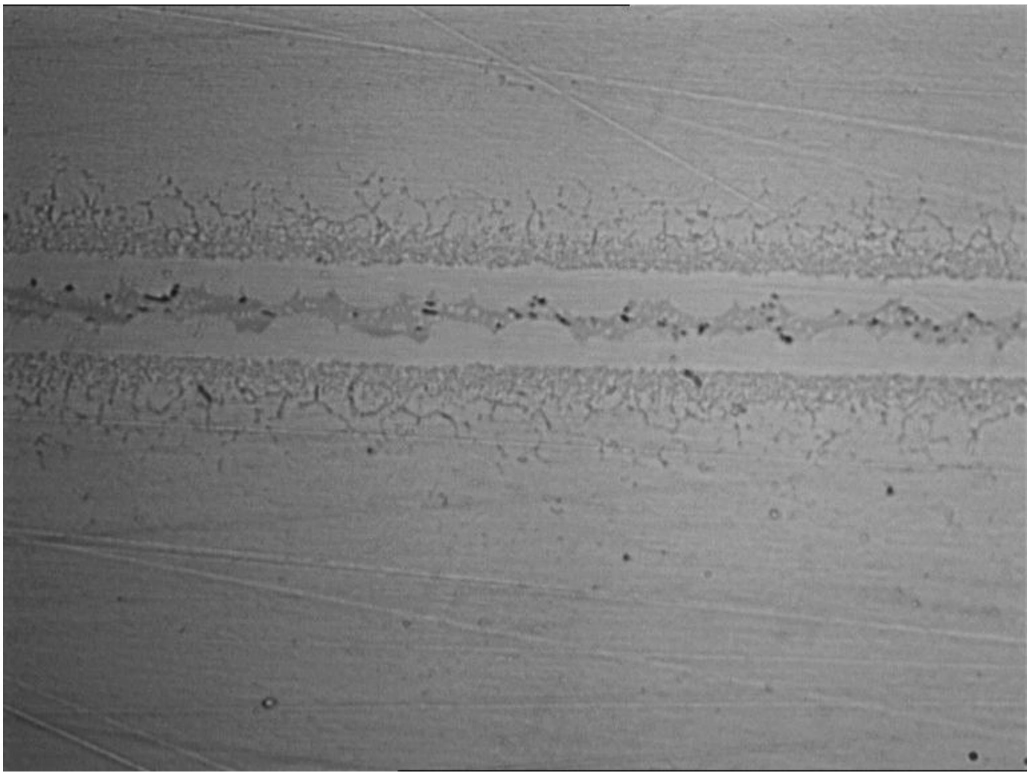


Figure 49. BNi-2 with 0 mm joint clearance. Visible reaction between BFM and base metal.

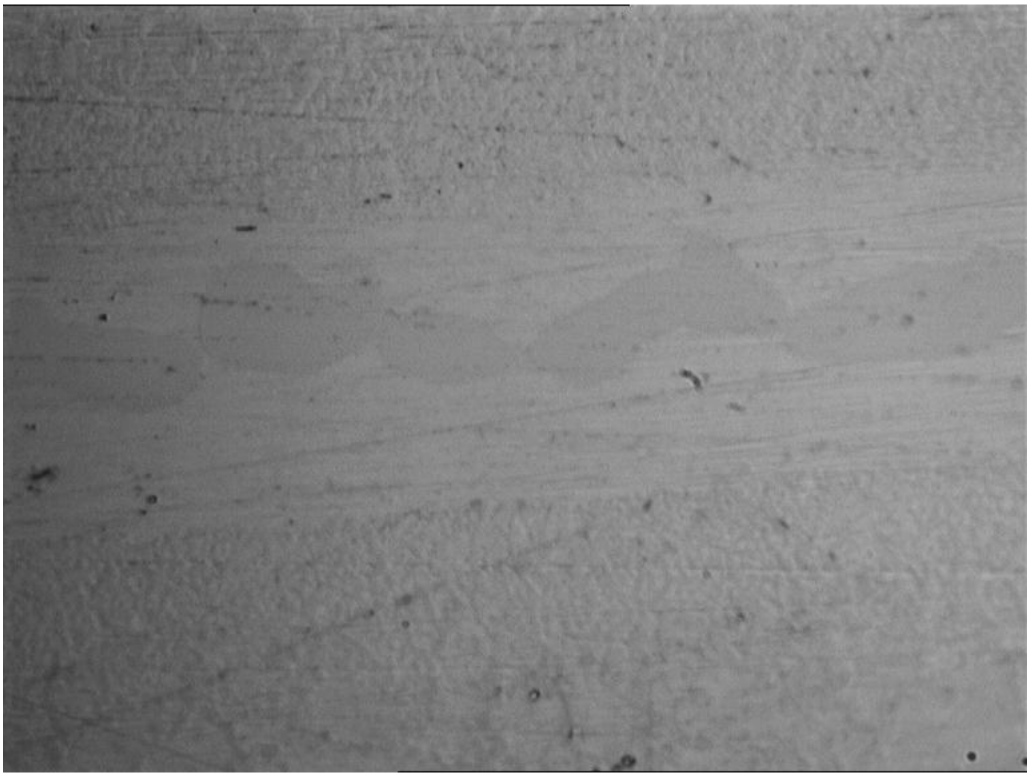


Figure 50. BNi-2 with 0 mm joint clearance. Highly magnified.

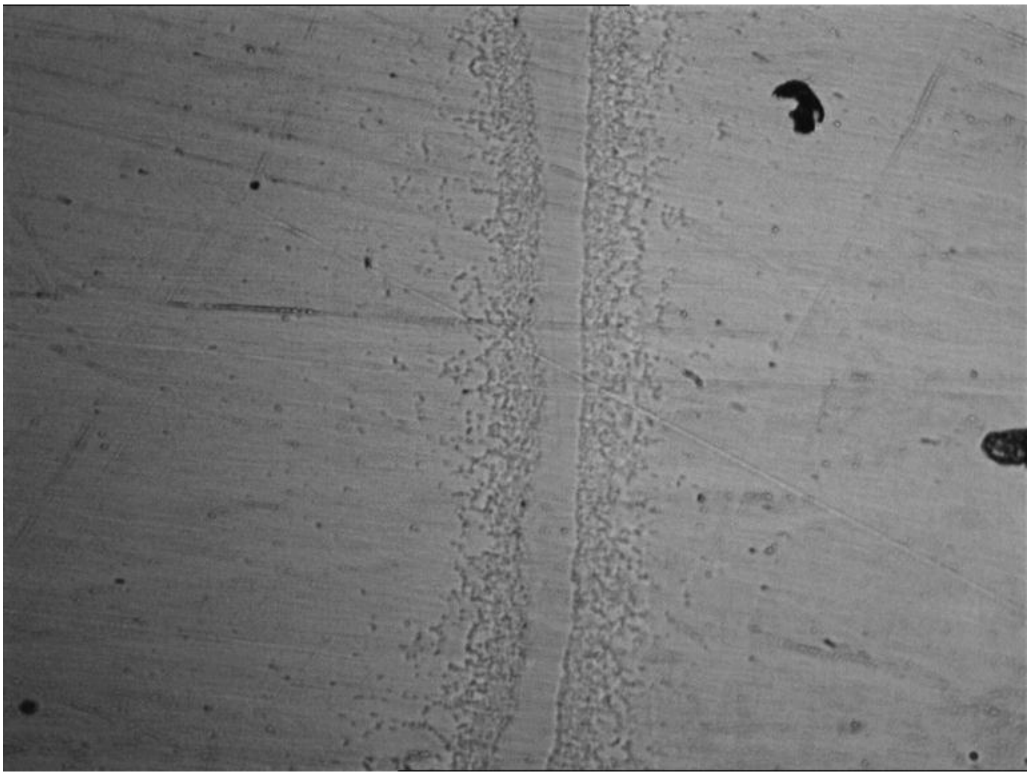


Figure 51. BNi-2 with 0 mm joint clearance. Joint end. Good filling of the whole joint length.