CHALMERS
UNIVERSITY OF TECHNOLOGY

Joining of non-ferrous metals

Bachelor thesis IMSX20

OSCAR SAMUELSSON

ISAK TILLBERG

DEPARTMENT OF MECHANICAL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2023
www.chalmers.se

Bachelor Thesis IMSX20

Joining of non-ferrous metals

Oscar Samuelsson

Isak Tillberg

Chalmers University of Technology

Gothenburg, 2023

Joining of non-ferrous metals

OSCAR SAMUELSSON
ISAK TILLBERG

oscar@utby.com

isaktillberg@gmail.com

Supervisor: Adam Skagius, Volvo Cars AB
Examiner: Christer Persson, Head of Division, Engineering Materials, Industrial and Materials Science, Chalmers University of Technology

Department of Mechanical Engineering
Chalmers University of Technology
SE-412 96 Gothenburg, Sweden
Phone No.: + 46 (0)31-772 1000

DEPARTMENT OF MECHANICAL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY, Sweden 2023

Preface

We would like to express our gratitude to everyone who has supported and been involved in the making of this report. A massive thank you to our supervisor, Adam Skagius, and the team at Volvo Cars for making this project possible and for the guidance throughout the entire project. We would also like to thank everyone who has helped us conduct welding and tensile testing at the Strength Test Lab and Sheet Metal Workshop at Volvo Cars in Torslanda.

We would also like to direct gratitude to Per Jansson at Comptech i Skillingaryd AB for the guidance and for providing rheocasted details for testing. Henrik Sköld at Metallfabriken EVO AB has supplied us with vacuum-assisted high-pressure die-casted details for the testing which we are very grateful for.

Christer Persson, our examiner at Chalmers University of Technology, has been of great help during the duration of the project.

Abstract

The subframe is a large component in a car and is important for meeting the cost, weight and sustainability targets. A light and cost-effective aluminium subframe is therefore interesting for future use. The joining of high-pressure die casted components and extruded aluminium beams was investigated in order to develop a geometrically complex and lightweight subframe. A literature study on possible joining methods and alternative casting processes were carried out and then possible design of joints were illustrated in the report. Mechanical testing of welded joints between components of different die-casting processes and extruded aluminium was conducted. Adhesive bonding, flow-drill screwdriving, hybrid joint of adhesive and flow-drill screwdriving as well as MIG-, TIG- and laser welding were recommended for continued research.

Keywords: Aluminium, Aluminum, Wrought, Die-casted, Extruded, High Pressure, Casting, Joining, Non-ferrous, Welding, Adhesive, Riveting, Flow-Drill, Rheocasting, Semi-Solid, Automotive, Subframe

Table of Contents

1 Introduction

1.1 Background

The goal when developing a car is to have cost-effective solutions that still perform according to the manufacturer's attribute requirements. In the case of Volvo cars, the attribute requirements are related to, e.g. safety, weight and sustainability. Different components of the car provide individual functions and therefore the requirements differ from component to component. Body Control and Road Contact is the department at Volvo cars responsible for the components which connect the car to the ground. One of these components, the subframe, is normally a large piece and is a crucial part in meeting the goals of the attribute requirements. Therefore, the subframe is important for the car to meet the weight and sustainability targets. With less weight, the car will need less energy to be powered, which is more environmentally sustainable.

A rear subframe is a critical component between the passenger compartment and the road loads. It acts like a mount for the suspension, and it reacts to the travel of the vehicle in corners, bumps, braking and acceleration. Due to its location under the car, it is subject to considerable environmental conditions and mechanical stresses. Depending on its attributes, such as size, material and type of car, the weigh may be somewhere between 14 to 35 kg (Aluminum Extruders Council, 2022). A typical subframe is the component to which the suspension, driveshafts, differential, and other components are connected. This can be seen in the figure below.

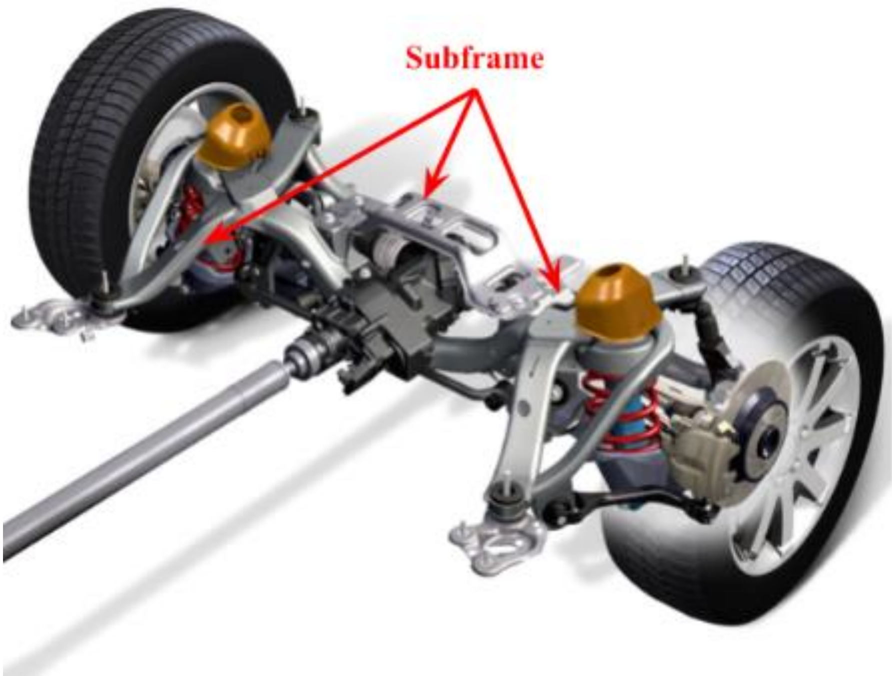


Figure 1, *Example of a body control unit from an old Volvo XC90*

Since weight is an important requirement in the automotive industry, aluminium and other non-ferrous metals are used for their low weight properties. One disadvantage of casted aluminium, which is commonly used in industry, is the high cost of aftertreatments such as heat treatment and milling operations. The milling of a low-pressure casted subframe is, according to Volvo cars, an expensive process which represents a major part of the component cost. The post-processing of the component is also a form of waste and if reduced, the component could be more sustainable.

At the moment there are two types of subframes used in the production of Volvo cars; stamped and welded steel, and low pressure die casted aluminium. Steel subframes are used for high production volumes, aluminium subframes are used in lower production volumes. For stamped and welded steel subframes there are high tool investments, but with high production volumes the part prices are relatively low. One upside of stamped steel subframes is that the rate of production is quite high. Casted aluminium subframes, requires time-consuming post processing in the form of heat treatment and machining, which make them expensive. The tool investments are relatively cheap compared to stamped steel which makes it a good process for low production volumes. Since there is up and downsides with both types, combining the positive aspects of both presents an opportunity to create a light and low-cost subframe. This could possibly be done by producing some of the complex shapes in cast aluminium and joining these with beams of extruded aluminium.

1.2 Aim

The aim of the project is to find a solution for Volvo Cars for a more economical way to manufacture a non-ferrous subframe. The subframe in question is currently made of stamped and welded steel and the project's main goal will be to find a way to manufacture a subframe from a non-ferrous metal without requiring costly post-processing.

1.3 Limitations

- This project will not be an in-depth study of aluminium castings or extrusions, but a study in joining of components made by these methods.
- No advanced strength analysis will be made.
- This project will not result in a definite method or design, but rather a couple of promising methods and examples of joint design.

1.4 Specification of issue under investigation

The subframe that will be analysed for the thesis work is made of stamped and welded steel. The company is interested in finding a solution that is lighter and preferably cheaper but is still able to meet all the requirements and agreements that Volvo Cars have today.

Since there is up and downsides with both types of subframes used today, combining the positive aspects of both presents an opportunity to create a light and low-cost subframe. This could possibly be done by producing some of the complex shapes in cast aluminium and joining these with beams of extruded aluminium.

The specific question under investigation is, how high pressure die-casted aluminium components can be joined with extruded aluminium beams to manufacture a complete subframe.

2 Methodology

An analysis of the current solutions for subframes at Volvo was conducted. Then as a baseline is set, information regarding joining methods and manufacturing processes of non-ferrous metals was gathered. This information was gathered by conducting an in-depth literature study. The joining methods or manufacturing processes with little information available was not in focus for this project. There was not a specific number of joining methods or manufacturing processes that was researched, the relevant information to be collected determined the future proceeding. The process of classifying the information regarding joining methods or manufacturing processes was done by Volvo Cars. Therefore, a close dialog with the supervisors at Volvo Cars helped determine what information could be discarded from the future work and what information was deemed relevant.

Once the theoretical knowledge of the areas was established, solutions that was of interest were tested and developed further. Some solutions were discarded for possible attributes that was not of interest for the company. This was also accomplished through close collaboration with persons of interest at Volvo Cars. If some solutions seemed to be a possible replacement for today’s subframe, they were tested in different areas. After sorting out the better solutions, some solutions were tested in different labs at Volvo Cars, in order to establish their performance.

When all the necessary information was gathered and a possible solution (or a couple of possible solutions) for replacing said subframe were been presented, a thesis report will be written according to Chalmers’ guidelines.

3 Literature study on joining methods for non-ferrous metals

An introductory literature study was conducted in order to obtain knowledge of different joining methods for casted and extruded aluminium. Most of the researched areas were recommended by the team at Volvo Cars, some were added as the study went along. A short presentation of the different joining methods is presented below.

3.1 Differences in mechanical properties

In order to set a baseline of what is known about casting aluminium, a small study was conducted. Low pressure casting is used in subframes today, high pressure die casting is an area of interest for future subframes.

3.1.1 Low Pressure Castings (LPC)

Since most of the alloys used in low pressure casting of aluminium are heated and melted under a flux of inert gas, the hydrogen pickup and oxidation of the detail is minimized. LPC generally show less quantities of defects, especially porosities due to air entrapment and turbulence during filling, than high pressure die-castings. (Nunes, Emadinia, Vieira, & Reis, 2022) In LPC, mould parts in sand and sand cores can be used to create internal passages which allows for a greater freedom of design. (Kridli, Freidman, & Boileau, 2021) Low pressure castings with permanent moulds generally obtain high strength and ductility. They are also considered weldable. (Graf, 2021)

3.1.2 High Pressure Die-Castings (HPDC)

In HPDC molten aluminium are pressed into a permanent mould at high speed and pressure. HPDC is capable of short cycle times making it more productive than LPC, the investment cost is generally higher, but this is offset by higher productions series. HPDC also has the ability to create parts with more complex geometry, thinner sections and better surface quality than LPC. (Nunes, Emadinia, Vieira, & Reis, 2022) Small tolerances are possible. The accuracy is better than most other casting processes, meaning that generally little to no machining is needed. One drawback of HPDC is limited ductility in the casted parts. (Sigworth, 2018) Another drawback is that the castings generally are not weldable or heat treatable. The high pressure and velocity in the injection process causes entrapped gases in the casting, making it unsuitable for welding and heat treatment. (Nunes, Emadinia, Vieira, & Reis, 2022) The design is limited by the use of permanent moulds, which consists of dies that can be opened and closed. The way the dies operate limits the freedom of design, especially when it comes to complex internal geometries. (Kridli, Freidman, & Boileau, 2021) A remedy to this limitation may be to use some kind of lost core method. The core is used to form an internal or undercut design feature and is then removed from the casting (usually dissolved or flushed out). (Cornacchia, et al., 2019)

3.1.3 Comment regarding continued research

Further research in the report will be regarding high-pressure die casting and not low-pressure casting, since Volvo Cars have sufficient information regarding the joining technologies possible with this type of material. According to Volvo Cars, the general properties of adhesive- and mechanical joining are the same, no matter if it is low pressure castings or high-pressure die castings.

3.2 Researched joining methods

A short presentation of the different joining methods that were investigated is presented below.

3.2.1 Friction Stir Welding (FSW)

Friction stir welding is a joining method that involves a rotating tool that melts the materials which makes them bond together. The tool is made from hardened tool steel if it is intended for aluminium bonding. When bonding aluminium by using FSW, the tensile strength in the welds could be affected by a decrease in up to 35% in some aluminium alloys. (Mallick, Joining for lightweight vehicles, 2021) It is possible to join dissimilar metals like aluminium to steel by using FSW. (Ananda Rao & Ramanaiah, 2019)

There are a number of benefits to using FSW rather than other welding methods, e.g., low distortion, no porosity, low shrinkage, no need for filler material and low energy consumption. It is also very easy to adjust the process since it mainly consists of three variables: pressure, tool rotational speed and tool traverse speed. There are some drawbacks to the joining method, one of great significance is the limitations in geometry due to the fact that the parts need to be rigidly clamped together, which is mostly fitting for long, straight and flat joints. Another is the relatively slow welding speed and that there is a need for finishing work since the tool exit- and entry hole needs to be filled in after welding. (Mallick, Joining for lightweight vehicles, 2021)

3.2.2 Metal Inert Gas Welding (MIG)

In MIG welding an electric arc is generated between the electrode and the base metal. The electrode is a metal wire which is consumed in the welding process and becomes the filler metal. The wire is automatically fed into the weld pool as the welding is done. To protect the process from the atmosphere an inert gas is streamed around the weld pool and electrode area during the process. (Mallick, Joining for lightweight vehicles, 2021) The possible joint types for fusion welding are butt and lap- or fillet joints. (Khurmi & Gupta, 2005)

The heat from the welding process creates a heat affected zone (HAZ). In this zone there is a risk of changing the metallurgical properties of the material. For example, work hardening and heat treatments may be more or less annealed. The HAZ becomes softer and weaker than the base metal. Depending on the type of alloy, a post weld heat treatment may be utilised to restore the material properties. (O'Brien & Sinnes, 2015)

When welding high pressure die-casted aluminium, porosity is a problem. There are gases, mainly consisting of hydrogen, trapped in pores in the casted detail. When welding, gases are released which causes porosity and low tensile strength in the welds. There are ways to remedy this, e.g., by degassing methods during welding or lowering the porosity in the casting (Ye, et al., 2022)

3.2.3 Tungsten Inert Gas Welding (TIG)

This welding technique works by a non-consumable tungsten electrode creating the electric arc to the parts that are going to be joined. The process uses an inert gas around the arc to shield and protect the weld pool. In some cases, filler metal is added by feeding a wire or a rod into the weld pool. The arc melts the filler metal as it is added to the weld pool. TIG-welding is a slower welding process than MIG-welding, but it has a better surface appearance considering no spatter is created. (Mallick, Joining for lightweight vehicles, 2021)

TIG-welding also faces the same difficulties with porosity in the welds when welding high pressure die-casted aluminium as MIG-welding. (Ye, et al., 2022) The same goes for the altered microstructure and the possible need for a post-welding heat treatment. (O'Brien & Sinnes, 2015)

3.2.4 Laser Welding

Laser welding uses a high-energy laser in order to melt the different details and then as the melt solidifies, join the parts together. The energy is focused on 0.1–1 mm diameter spot which produces an energy density of 100–110 kW/cm2. Inert shielding gas may be necessary to prevent oxidation or degradation of the welds. (Mallick, Joining for lightweight vehicles, 2021)

Advantages of the welding process are the deep penetration of the weld, narrow heat affected zone, low heat distortion and a high welding speed (50-100 mm/s). Laser welding does not require physical contact to the weld area, the laser beam can be manipulated using mirrors and it can be transmitted using fibre optic cables, which enables more complex welds in very complex geometries. (Mallick, Joining for lightweight vehicles, 2021)

There are a few disadvantages with laser welding, e.g. the need for very precise joint fit up for the weld and the high running- and investments costs. Joining aluminium with laser welding requires more power due to the high reflectivity and thermal conductivity of the metal. The high reflectivity reduces the absorptivity of the laser energy, and the high thermal conductivity leads to rapid heat dissipation from the weld area. Laser welding faces the same problems as arc welding with porosity in die-casted aluminium parts. (Mallick, Joining for lightweight vehicles, 2021)

Most of the joint types used in conventional fusion welding processes can also be used in laser beam welding. Filler wire can be used to make multiple passes when welding thick material, to control the weld bead geometry and to prevent undercutting. (Mazumder, Webber, & Paura, 2011)

3.2.5 Spot Welding

3.2.5.1 Friction Stir Spot Welding (FSSW)

Friction stir spot welding is a welding technique that is very similar to friction stir welding. The difference between them both is that FSSW does not traverse laterally, like FSW does, but joins the part by spots. FSSW is mostly usable for lap joints of sheets. (Mallick, Joining for lightweight vehicles, 2021)

A spinning tool is plunged into the upper sheet with axial force and counteracted by a backing plate below the other sheet, creating frictional heat at the desired spot. The heat softens both sheets and as the rotating tool moves downward, the softened material starts to move vertical. This creates a metallurgical bond in the interface between the two sheets. (Mallick, Joining for lightweight vehicles, 2021)

3.2.5.2 Resistance Spot Welding (RSW)

A weld is created by having electric current pass through two electrodes, creating an intense localised heat which melts the interface between two sheets. During the cooldown of the material a welding nugget is created. The immense pressure from the electrodes during the welding process keeps the sheets together. The bigger the nugget, the stronger the weld. The parameters that control the size of the nugget include weld current, hold time, welding time and the force from the electrodes. Other conditions that have an influence on the nugget is the fit-up between the sheets, the surface condition and the design of the electrode tip. (Mallick, Joining for lightweight vehicles, 2021)

Advantages of using RSW is that it is a fast operation, low costs, no need for filler materials and that the joining is internal and is therefore not visible from the outside. (Mallick, Joining for lightweight vehicles, 2021)

3.2.5.3 Laser Spot Welding

This method is a non-contact process that uses a laser beam to create spot welds in order to join the parts. The laser is focused on a spot where the light then is absorbed by the metal which leads to melting of the materials. The melted metal flows, solidifies and a spot weld is created. It is a very fast process that may be repeated to reach desired bond strength and depending on the thickness of the material. (IPG Photonics Corporation)

Laser spot welding requires precise joint fit up and is suitable for lap joints. As for laser welding, laser spot welding also faces porosity issues when welding cast aluminium. (Mallick, Joining for lightweight vehicles, 2021)

3.2.6 Brazing

Brazing is a process in which a filler metal is applied to the joint, the filler material is melted and bonds with the base metal to create the joint. Unlike welding, only the filler metal is melted. (Devienne, 2014) However, in aluminium the melting point of the filler metal is very close to the melting point of the base material. Cast aluminium generally has a lower melting temperature than wrought aluminium, making it unsuitable for brazing. (O'Brien & Sinnes, 2015)

3.2.7 Self-Piercing Riveting (SPR)

Self-piercing riveting is a joining method for sheets of materials. A semi-tubular rivet is forced through the top layer, the rivet then flares out in the bottom layer without penetrating completely through it. The flaring of the rivet creates a secure connection of the material sheets. (Mallick, Joining for lightweight vehicles, 2021)

Self-piercing rivets can be used for dissimilar metals including both wrought and cast aluminium, in aluminium the maximum joint thickness is 10mm. They have a high fatigue strength compared to resistance spot welded joints and the cycle time for each rivet is very fast. (Mallick, Joining for lightweight vehicles, 2021)

There are two main drawbacks with SPR in this application, since the method is only used for sheets in lap joints the design choices are limited. The other drawback is the need for tools on both sides of the joint. This means that access is needed on both sides of the joint, further limiting the design choices. (Mallick, Joining for lightweight vehicles, 2021)

3.2.8 Flow-Drilling

3.2.8.1 Flow-Drill Threading

In flow drilling a rotating tool is pushed through a stack of material, creating a hole. Unlike a regular drill bit the flow drill has a conical tip with no cutting edge. The heat from the friction and thrust softens the material around the tool which is pushed out of the hole as the tool penetrates the bottom layer. This effect creates a bushing on the bottom material layer. The bushing is then threaded and a screw is used to fasten the joint. The bushing extends the thread engagement and creates a stronger joint. Flow-drilling can be used to join dissimilar metals and is suitable for both wrought and cast aluminium. This process only needs access from one side of the workpiece. (Felinks, Overberg, Sarafraz, Walther, & Biermann, 2021)

3.2.8.2 Flow-Drill Screwdriving (FDS)

Flow-drilling can also be done with flow-drilling screws, which consists of a conical tip like the flow drill, a threaded shank and a head with a drive system. It works like a flow-drill but also creates the threads and is torqued to a pre-set value. Flow-drilling screws can also be used to join both wrought and cast aluminium. The process only requires access from one side. (Mallick, Joining for lightweight vehicles, 2021)

3.2.9 Mechanical Joining

3.2.9.1 Screw Connections

Mechanical joining by using nuts and bolts have been used for a long time in the automotive industry. The basis of the method is that different parts are joined by making a hole and then the bolt and nut are tightened together. Instead of a nut, a threaded hole can be used. The method has its benefits, e.g., it can be disassembled, but there are more drawbacks to using screw connections in the automotive industry. One of these drawbacks is that it is considered too slow for assembling body components. Another being that they may require drilling, or stamping of holes, threading and precise fit-up. (Mallick, Joining for lightweight vehicles, 2021)

3.2.9.2 Self-Tapping screws

Another possibility is to use self-tapping screws which create their mating thread as they are screwed into the material. However, pre-made holes and accurate fit-up is still needed. (Messler Jr, 2004)

3.2.10 Adhesive Bonding

Joining by adhesive bonding is an interesting method, especially for hard to weld materials such as high pressure die casted aluminium. It provides high stiffness and good fatigue resistance, since the stress is distributed through the whole surface area of the joint and no stress concentrations are created. Correct joint design is crucial for the adhesive to perform correctly, the surface preparation and curing is also very important. Bond thickness and overlap length are also crucial for the performance of the joint. Adhesive joints generally have low peel strength, this could be an issue regarding crashworthiness. To help remedy this problem, reinforcement by rivets or spot welds can be utilised. (Mallick, Joining for lightweight vehicles, 2021)

3.2.11 Compilation of joint design for the joining methods

Joining method	Joint design features
Friction Stir Welding (FSW)	Only one dimensional joining possible, complex geometries are not able to be joined using this method.
Metal Inert Gas Welding (MIG)	Different types of butt, lap and fillet joints are possible.
Tungsten Inert Gas Welding (TIG)	Different types of butt, lap and fillet joints are possible.
Laser Welding	Different types of butt, lap and fillet joints are possible, but requires high precision joint fit-up.
Friction Stir Spot Welding (FSSW)	Only works on stacked materials.
Resistance Spot Welding (RSW)	Only works on stacked materials.
Laser Spot Welding	Only works on stacked materials.
Brazing	-
Self-Piercing Riveting (SPR)	Only works on stacked materials.
Flow Drill Threading	Only works on stacked materials.
Flow-Drilling Screwdriving (FDS)	Only works on stacked materials.
Screw Connections	Only works on stacked materials.
Self-Tapping screws	Only works on stacked materials.
Adhesive Bonding	The bond has the highest strength in stacked materials.

Table 1, *Joint design features for the different joining methods*

3.3 Finding solutions that are applicable for the subframe

In order to find solutions that are suitable and applicable for a subframe, an elimination of non-applicable joining methods were conducted.

3.3.1 Elimination of joining methods

To decide which joining methods are interesting for continued research, a summary of the introductory literature study was conducted and presented. The presentation was held for the supervisors and team members at Volvo Cars, a following discussion helped clarify which joining methods are interesting to continue working with.

In the table below, results of the elimination will be given. A short explanation of why the decision was made for each material will also be given.

Joining method	Further research	Reason for elimination
Friction Stir Welding (FSW)	NO	Not suitable for this subframe geometry
Metal Inert Gas Welding (MIG)	YES	-
Tungsten Inert Gas Welding (TIG)	YES	-
Laser Welding	YES	-
Friction Stir Spot Welding (FSSW)	NO	Access is needed from two sides
Resistance Spot Welding (RSW)	NO	Access is needed from two sides
Laser Spot Welding	NO	Very limited information regarding the subject
Brazing	NO	Not suitable for die-cast aluminium/not enough information available
Self-Piercing Riveting (SPR)	NO	Access is needed from two sides
Flow Drill Threading	NO	Not a viable option since only a thread is made, mechanical fastening is required
Flow-Drill Screwdriving (FDS)	YES	-
Screw Connections	NO	Well known, no more research needed
Self-Tapping screws	NO	Well known, no more research needed
Adhesive Bonding	YES	-

Table 2, *Elimination of joining methods after consulting with Volvo Cars*

Friction stir welding was eliminated due to the issue with complex geometries and therefore it is not that suitable for this subframe. Friction stir spot welding, resistance spot welding and self-piercing riveting were also eliminated because they require access from both sides which will limit the design too much. The elimination of brazing was done due to it not being suitable since the temperature of the filler metal is close to the melting point of cast aluminium. Flow-drill threading does not provide a whole bond, only a thread, which then requires a mechanical fastening in the form of, e.g., a screw. The team and supervisors at Volvo Cars felt that the research done on mechanical joining by screws and screw connection was sufficient and no additional information was needed, hence, it was eliminated.

3.4 Further research for implementing the joining methods

After the elimination of joining methods, it was determined that further research on a couple of joining methods needed to be done. Since the mentioned welding techniques, that were not eliminated previously, all had problems with porosity while welding in high pressure die-casted aluminium, further research was necessary in order to find solutions to remedy this problem. Further research was also conducted on adhesive bonding and flow-drill screwing.

3.4.1 Solutions to remedy the porosity problems for welding

3.4.1.1 Slower welding speed for MIG- and TIG-welding as well as Laser Welding

Degassing the weld pool without additional tools or devices is done by having the arc move slower. The longer the pool stays in liquid form, the more it will degas. This will generally increase the stability of the process since MIG-welding at low speed has a lower sensitivity to the formation of gas pockets. TIG-welding is generally better of degassing hydrogen pockets in the weld pool than MIG-welding. It has been proven that generally low porosity can be obtained by welding pressure die cast parts with low gas contents. (Wiesner, Rethmeier, & Wohlfart, 2005)

For laser welding it has been proven that it is possible to obtain high weld quality using welding speeds of up to 10 m/min, however having slower speeds will generally result in better weld quality. Laser welding requires a vacuum in the welding chamber to extract the gas from the weld pool during welding. For laser welding the gas content needs to be very low in order to obtain a good weld quality. (Wiesner, Rethmeier, & Wohlfart, 2005)

In the case of MIG- and TIG-welding, AlSi alloys were proven to cause less porosity in the welds than the AlMg alloys that were tested. However, for laser welding holes and defects in the weld was experienced in both alloys. (Wiesner, Rethmeier, & Wohlfart, 2005)

3.4.1.2 Ultrasonic Frequency Pulse (UFP) degassing while welding

One way to remedy the porosity problems that affect welding could be to use an ultrasonic frequency pulse degassing method. The degassing method works by having a UFP device generate a UFP signal that mixes and stirs the encapsulated hydrogen gases in the casted aluminium part. The UFP signal makes the hydrogen atoms/ions in the weld pool grow rapidly which enables the formation of larger hydrogen “bubbles” which helps them escape and thus forming a less porous weld. The method has been proven to increase the tensile strength of the weld by 85% compared to MIG-welding without UFP and reach a tensile strength of 94.1% of the die-cast aluminium base metal. It is suitable for use in MIG- and TIG-welding. (Ye, et al., 2022)

3.4.1.3 Electromagnetic supported degassing while welding

Another way of reducing the porosity problems in welding of die cast aluminium is the use of electromagnetic supported degassing. This method has been researched for laser welding with the very promising results of up to 70% porosity reduction. To degas the melt, an electromagnetic system is used to add additional buoyancy to the gases in the pores, making them release quick enough not to be trapped in the solidified weld. The research found regarding this process has been conducted for laser welding, however, it would be interesting to know if it can be used for MIG- and TIG-welding. (Hilgenberg, Rethmeier, & Fritzsche, 2020)

3.4.1.4 Ultrasonic Welding

Ultrasonic welding is a solid-state welding process that produces coalescence through the application of moderate clamping forces and high-frequency vibratory energy. The frictional action from the vibrations caused by the ultrasound, disperse oxides and contaminants which results in metal-to-metal contact and great bonding. Since there is no melting in the process, there is a possibility to join thin and thick sections and there is little need for surface preparation and degreasing of parts. Ultrasonic welding is possible for all aluminium alloys, however, only parts of a thickness up to 3 mm are possible to spot- or seam weld using ultrasonic welding. (Berube, 2018) Some advantages of ultrasonic welding are the pure microstructure that is free from defects, such as pores and solidification cracking. Fine equiaxed grain structure with good mechanical properties is obtained from the severe plastic deformation from the welding process. There are some limitations of the process, e.g., only lap joints are possible and high tooling costs for the clamping tools. (Thapliyal, 2021)

3.4.2 Solutions for lower gas content in casted details

3.4.2.1 Vacuum-assisted High Pressure Die Casting (V-HPDC) and Pore Free die casting

The problems of welding high pressure die-casted aluminium is generally caused by porosity in the casted material, which contain mainly hydrogen gas. (Ye, et al., 2022) Conventional high pressure die-casting causes porosity problems due to entrapped gases in the casting from the turbulence during the filling process. Vacuum assisted die casting and pore free die casting are two methods that can significantly reduce the porosity of die casted components, making them both weldable and heat treatable. These methods can also be combined as vacuum assisted pore free die casting. In vacuum assisted die casting, the inner gases in the casting can be reduced. But for the casting to be weldable, high vacuum assisted casting is necessary. High vacuum casting requires expensive investments and pore free die casting is another option. In pore free die casting, oxygen gas is injected during the die casting process, it then reacts with the molten aluminium. This reaction creates a vacuum in the die, creating similar results as the high vacuum process at lower investment costs. (Kang, et al., 2020)

One example of vacuum assisted die casting is the High-Q-Cast process. A high vacuum is achived in the die before the metal injection. Due to the vacuum, porosity is minimized and the castings are weldable and heat treatable. Depending on the alloy used, this process can also produce castings of high ductility, capable of high energy absorbtion which is nesessary for good crash preformance. Welding of castings produced by this method can be easily done with good results using standard equipment such as mig-welding. (Brown & Burton, 2007)

3.4.2.2 Squeeze casting of aluminium

Squeeze casting is a method where molten aluminium is solidified under pressure in a closed die. The pressure is introduced directly after the molten alloy starts to solidify and is stopped once the entire casting has solidified. Since the molten aluminium is in full contact with the mould, the surface quality of the casted part is very good. The high cooling rate of the process results in a fine-grained microstructure and very good mechanical properties. One downside of squeeze casting is a limitation in very complex geometries. However, the method is economical, the porosity in the detail is low, very high strength is obtained and is suitable for revealing fine-grained microstructures. (Bayraktar & Hekimoglu, 2021) Another advantage to squeeze casting is the ability to use sand cores to create great internal details of the parts. The process creates details with low porosity. (Kridli, Freidman, & Boileau, 2021)

3.4.2.3 Semi-Solid casting of aluminium

When fully melting aluminium in order to die-cast, the problem with porosity can occur. One way to remedy this is to cast during a non-liquid state of aluminium. Semi-solid casting is a process that involves a filling a mould with aluminium in a partially molten state. It should contain 60% liquid and the remaining 40% should be remained solid and homogeneously dispersed throughout the mixture. The mixture is then injected at high rates and in laminar flow into the die cavity. Due to its low casting temperature the shrinkage is low, the gas porosity is almost absent and the microstructure is very fine. (Kridli, Freidman, & Boileau, 2021) Semi-solid casting creates products with exceptional soundness and therefore the strength, ductility and fatigue resistance are high and the method creates fully weldable products. (Midson, Pucella, & Côté, 2015) One of these semi-solid casting processes is rheocasting. (Kridli, Freidman, & Boileau, 2021)

3.4.3 Further research on Adhesive Bonding

Adhesive bonds generally consist of a metal adherent, a substrate, a primer, an adhesive and an oxide layer. The metal adherent is a body that is held on to another body using adhesive. The substrate is a material on the surface of the metal on which a substance containing adhesive is spread on. The primer is a coating that is applied to a surface before the application of the adhesive in order to improve the performance of the bond. The adhesive itself is a substance that is capable of bonding materials together by surface attachment. Lastly, the oxide layer is a layer of oxidized aluminium that is created when aluminium is exposed to air. The structure of the bond can be seen in the figure below. (Burt, 2018)

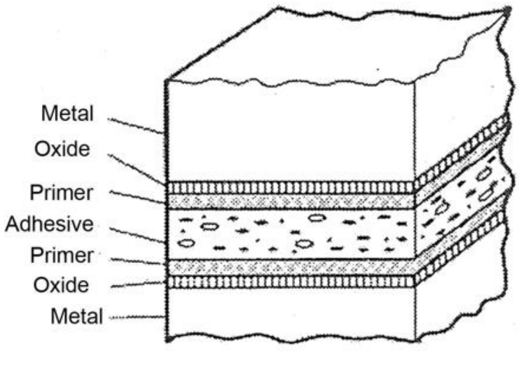


Figure 2, *Composite structure of typical metal-to-metal bonded joint* (Burt, 2018)

In order to obtain a good bond, the surface condition is important. Generally surface treatments are required to improve the adhesive bonding. Impurities and foreign molecules need to be removed and then avoided as further contamination. The main aims of the surface pre-treatments are to remove contaminants, maximize the molecular contact between the adhesive and substrate, and to generate a stable surface topography that is optimal for mechanical interlocking. (Burt, 2018)

There are seven different types of adhesives available; solvent based, water based, liquid, powder, film, solid extruded forms and paste. Depending on the porosity of the material, the viscosity of the liquid adhesive may vary to obtain a good joining. To ensure an even, flat and continuous bond, adhesive films might be the best option. Adhesives are also classified as thermosetting- and thermoplastic resins. Thermoplastic resins are long linear chains with a generally low cross-linking between the chains. The resin can be heated and to be softened and then hardened as it cools down. They are usually not adequate for load-bearing and structural applications but can be blended with thermosetting resins for more suitable properties. Thermosetting resins have a longer reaction and thus forms a more rigid and cross-linked structure. The resin cannot be softened by heating and is permanently hard. Thermosetting resins, e.g., epoxy- and phenolic resins, are the used the most in metal structural bonding and may require heat to start the curing process. (Burt, 2018)

Some limitations of adhesive bonding are that there may be a need for expensive jigging if heat, high pressure and time are crucial for curing the adhesive. Heating some aluminium alloys in order to cure the adhesive may increase the sensitivity to intergranular corrosion. An extensive cleaning of the bonding area is required for the best bonding, and the area needs to be protected from contamination until it is bonded. The peel- and impact strength of the bond is often more limited than the tensile strength. (Burt, 2018)

Some advantages of the bond are that the load is evenly distributed and the joint design can often be simplified. The fatigue characteristics and resistance of sonic vibrations are superior to other joining methods. A bond can be made between pieces of very different thickness and the adhesive seals the environment. (Burt, 2018)

For joining of load bearing parts in a subframe, a structural adhesive should be used. Structural adhesives generally have a strength of 7-40 MPa in overlap shear load bearing. For use on metals, epoxies generally have the best properties, and this also seems to be the case for the properties required in a subframe. (3M Company, 2012) As an example of a structural adhesive, the crash optimized adhesive DuPont Betamate 1496 Has a tensile strength of 30 MPa and a shear strength of 24 MPa. (Uprapakam Ramakrishnan & Mallick, 2022)

3.4.4 Further research on Flow-Drill Screwdriving (FDS)

A general description of the flow-drill screwdriving process has been made in section 3.2.8. In this section the research will be focused on evaluating if FDS is a viable method for joining structural components of a subframe.

Compared to a regular screw, the flow drilling screw enables a higher strength joint due to the draught formed when the screw penetrates the material. The threads fit tight up against the screw, making the screw joint waterproof and gas tight. Since heat is developed in the material, the drought shrinks around the screw when the process is finished. This makes the thread even tighter and provides a high dynamic safety. The heat developed in the process is not high enough to cause problems with heat treatments. (EJOT GmbH & Co. KG)

Another advantage of this process is that there is no need to line up holes, since pre-made holes are not necessary. Flow drilling screws only need access from one side of the component, making joining of hollow profiles possible. (EJOT GmbH & Co. KG)

Depending on the alloy of the parts to be joined the maximum material thickness may vary. For many aluminium alloys, material thicknesses up to 5mm can be penetrated without pre made holes. For thicker material (and also depending on the mechanical properties), clerance holes may be needed in the upper sheet of the stack. Pre-made holes for the bottom sheet may also be nessecary. To ensure good results, it is recommended to conduct an application study and evaluation in the specific case. (EJOT GmbH & Co. KG)

One downside of the flow drill screw is its low shear strength in comparison to adhesive, when tested, a lap joint between two aluminium sheets made by a flow drill had a shear strength of 5,9kN. When the same type of joint was reinforced with a polyurethane adhesive, the shear strength almost doubled. (Li, Jiang, Zhang, Luo, & Wu, 2022)

In another test, the peel strength of flow drill screws where investigated. A coach-peel test was conducted for sheets of aluminum 6082-T6 with different thicknesses. For 3mm thick sheets joined by one M5 flow drilling screw with no clearance hole, the average maximum load was 5162N. (Huang, Chen, Sung, & Pan, 2018)

3.4.5 Combining FDS and Adhesive

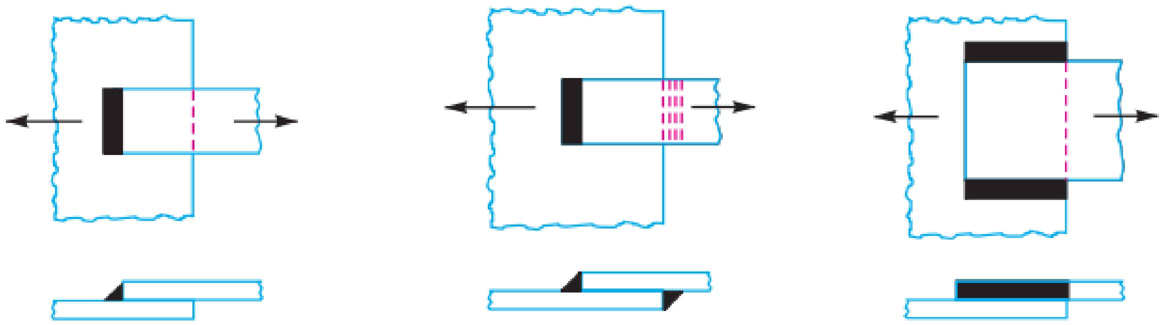
To remedy the problems concerning the peel- and impact strength of adhesive bonding and the low shear strength of flow-drill screws, a hybrid bond can be created. It has been shown that implementing adhesive to FDS joints in different commonly used aluminium alloy sheets used in structural and cover parts in the automotive industry, can greatly improve some mechanical properties of the joint. The adhesive in the joint increased the maximum tensile force and failure distance of the FDS joints. However, during high-speed tensile conditions the adhesive showed a severe tear and partial peeling from the aluminium sheets. The screws were completely peeled from the lower sheets, without sheet fracture under the same conditions. It should be stated that the maximum tensile force increased with an increasing joint thickness. (Li, Jiang, Zhang, Luo, & Wu, 2022)

In a test conducted on steel plates it was shown that a hybrid bond of adhesive and FDS remedied the problem with the low shear strength of flow-drill screws and greatly improved the problem concerning low peel strength in adhesive bonds. (EJOT GmbH & Co. KG)

3.5 Joint design – general information and examples

3.5.1 Design of MIG- and TIG-welds

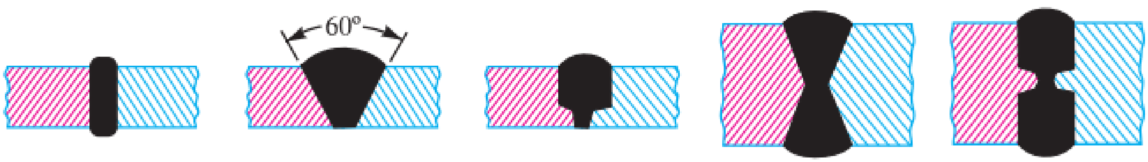
There are different types of weld joints for arc welding, butt and lap or fillet joint. Lap or fillet joints are obtained by overlapping a plate and then welding it in place. The lap or fillet joint can be in different styles, single transverse, double transverse, or parallel fillet joint, illustrated in figure 3. Single transverse fillet joints have the disadvantage that the end of the plate that is not welded can warp and buckle out of shape. (Khurmi & Gupta, 2005)



(a) Single transverse. (b) Double transverse. (c) Parallel fillet.

Figure 3, *Types of lap or fillet joints.* (Khurmi & Gupta, 2005)

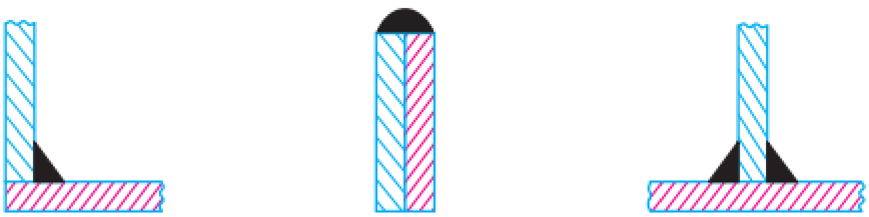
The other type of joint is butt joints, which is produced by welding edges together. If the material is less than 5mm thick bevelling is not needed for obtaining a good weld. However, f the thickness is between 5mm to 12.5mm, then bevelling into V. or U-grooves is required on both ends. The different styles of butt joints are square butt joint, single V-butt joint, single U-butt joint, double V-butt joint and double U-butt joint, which are illustrated in the figure below. (Khurmi & Gupta, 2005)



(a) Square butt joint. (b) Single V-butt joint. (c) Single U-butt joint. (d) Double V-butt joint. (e) Double U-butt joint.

Figure 4, *Types of butt joints.* (Khurmi & Gupta, 2005)

Other types of joints that can be used when welding are corner joints, edge joints and T-joints, which are illustrated in figure 5. The main considerations when selecting a weld type is the shape of the component, the thickness of the part and the direction the forces are applied. (Khurmi & Gupta, 2005)



(a) Corner joint. (b) Edge joint. (c) T-joint.

Figure 5, *Other types of welded joints.* (Khurmi & Gupta, 2005)

The stress is spread uniformly over the joined area, and the load is distributed uniformly along the entire weld. Generally, butt joints are designed for compression and tension, parallel fillet joints for shear strength and transverse fillet welds for tensile strength. (Khurmi & Gupta, 2005)

3.5.2 Design of Laser welds

Most of the joint types used in conventional fusion welding processes can also be used in laser beam welding. However, the laser beam is focused in a very small diameter spot, making the fit-up tolerance much more critical than for typical fusion welding. Filler wire can be used to make multiple passes when welding thick material, to control the weld bead geometry and to prevent undercutting. (Mazumder, Webber, & Paura, 2011)

3.5.3 Design of Adhesive joints

To obtain a good performance of an adhesive bond there are a few things to consider, one being the design to create a joint that distributes stress evenly to have a strong and reliable joint. The design of the joint should be optimized for the adhesive and not the other way around. In the figure below there are a few different types of joints.

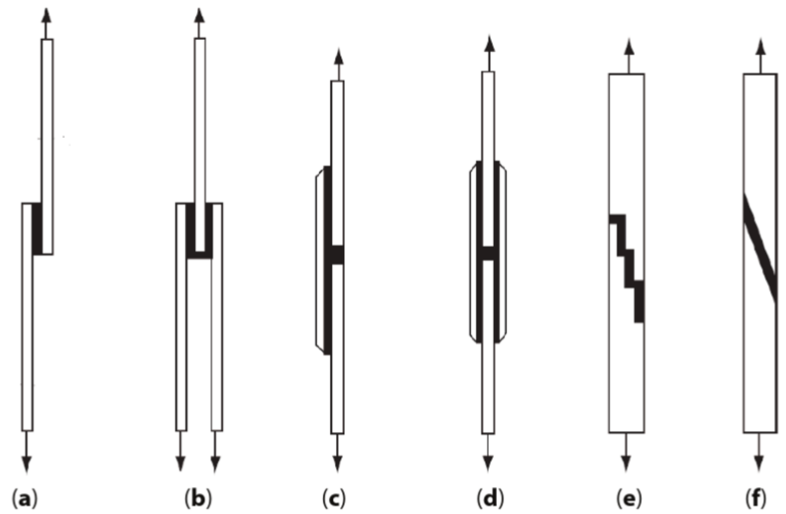


Figure 6, *Basic bonded joint designs: (a) single lap joint, (b) double lap joint, (c) single strap joint, (d) double strap joint, (e) stepped lap joint, and (f) scarf joint.* (Mallick, 2020)

The simplest joint is the single lap joint where the load transfers through a distribution of shear stresses. However, when tensile loads are applied a bending moment is generated at the adhesive joint since the ends are not along the same line. This moment creates a distribution of peel stresses and axial stresses, which all exhibits peak values close to the end of the lap. The double lap joint eliminates much of the bending action and peel stresses that the single lap joint exhibits. There are still stresses affecting the joint, but they are greatly reduced. There are however some limitations in geometries when having double joints. (Mallick, Optimization of Structural Adhesive Joints, 2020)

Bonded strap joints, both single and double, improves the joint strength compared to the single lap joint, but may not be suitable for all joints depending on geometry. Stepped lap and scarf joint have the possibility to produce high joint strength, but since difficult machining the steps and scarf angles is required, the advantages are overshadowed. (Mallick, Optimization of Structural Adhesive Joints, 2020)

3.5.4 Design of Flow-Drill joints

FDS is a method that requires stacked materials in order to create a bond. (Mallick, Joining for lightweight vehicles, 2021) This is limiting the joint design and is mainly suitable for lapped and strapped joints, as are described in previous chapters.

3.5.5 Design of combined Adhesive and Flow-Drill joints

Both adhesive and flow-drill screws have a limited joint design and the combination of them is limited as well. Generally, the joint will be a strapped or lap joint, with stacked materials. In order to obtain good bond qualities, the joint should be designed for low peel loads.

4 Current study on solutions for a non-ferrous subframe

The conversion of an existing subframe, the implementation of joint design and mechanical testing of welded joints were carried out and summarised in the following chapters.

4.1 Examples of joint design on a converted section of a subframe

In this chapter, the design limitations and guidelines for the different joining techniques was described. To exemplify the different joints a CAD-model of a stamped and welded steel subframe from a Volvo car in production today has been used. To simplify the examples, only a section of the subframe was used and some features have been removed. The model has been adapted from stamped and welded parts to one single high-pressure die casted piece which is to be joined to a crossbeam. This part has not been designed to be an actual part for production or analysis, the only purpose is for exemplifying the joint designs.

4.1.1 Converting a stamped steel subframe into a HPDC subframe

In the figure below, the existing subframe is shown, complete with bushings.

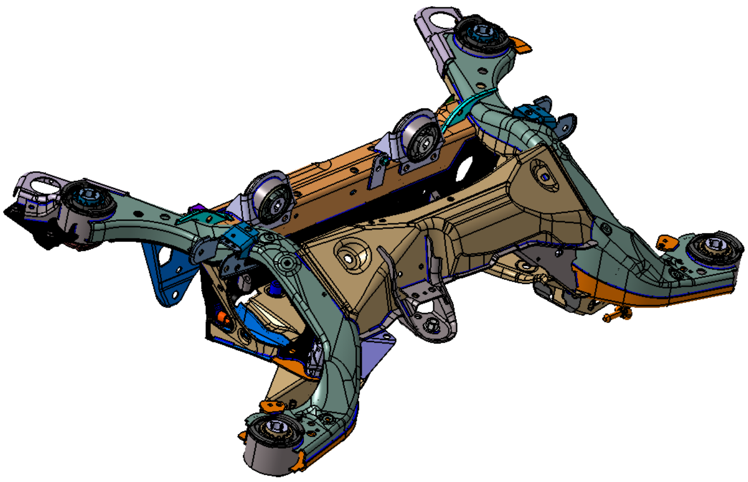


Figure 7, *Existing stamped and welded steel subframe from an XC40*

The subframe was then sectioned into a smaller part to simplify the joint design, shown in the figure below. However, this section still contains examples of a majority of the features found in the complete subframe.

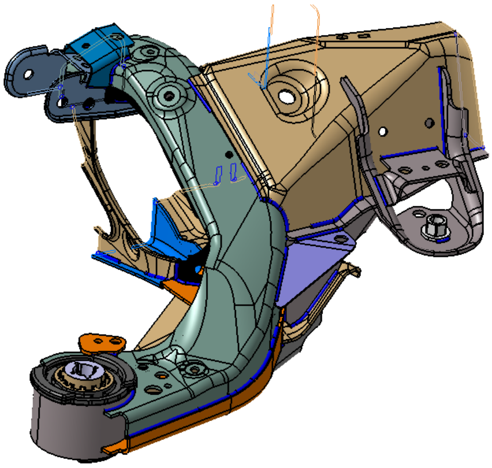


Figure 8, *Section of the existing subframe*

The subframe section was then converted to a high-pressure die-casting, containing as many features as possible. Note that if the whole subframe was adapted for casting, the casting would be continuous all the way towards the rear bushing (along the green beam in figure 7). Also note that this component is not a final design, but only used to visualize the joint designs of the different joining methods. The component is shown in the figure below and in appendix 1 & 2.

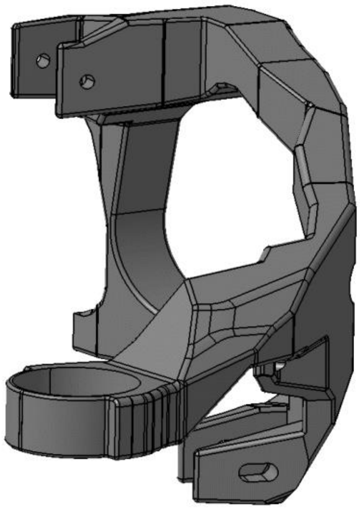


Figure 9, *HPDC-converted section of the XC40 subframe*

4.1.2 Example of a welded joint

The HPDC detail was adjusted in order to have an easy fit up to an extruded beam. A straight cut can be made on the extruded profile and the seam is then welded, as is illustrated by the blue line in the figure below. Note that this design of the die-casted profile is not very refined but can be used to give a good understanding of how a joint in this section can be done. More illustrating images of the welded joint can be found in appendix 3-5.

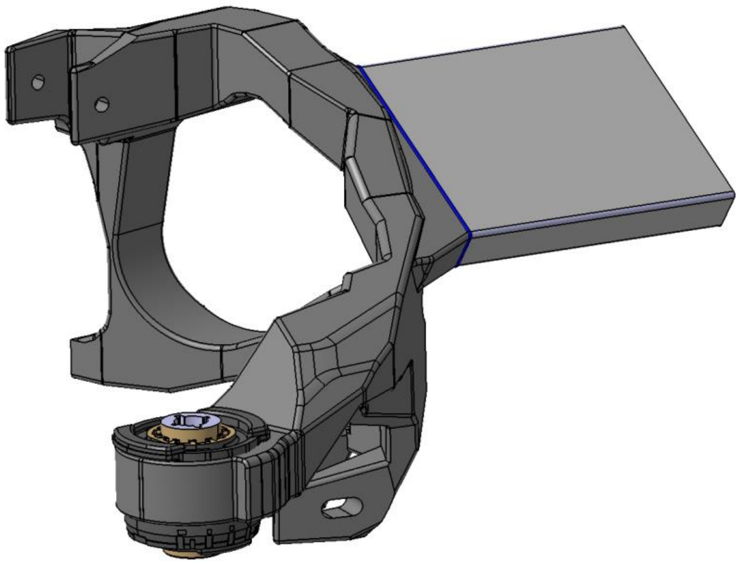


Figure 10, *Example of a welded joint*

4.1.3 Example of an adhesive joint

In order to create a joint that can absorb as much stresses as possible, a three-sided lap joint was created with adhesive applied to all faces of the joint. Since peel stresses are the limiting factor to an adhesive joint, the joint was designed to minimize peel stress. The two plates going down the sides around the extruded profile is there to counteract the peel stresses that can occur in the upper part of the joint. When the extruded profile is loaded with forces perpendicular to the upper part of the profile, the side plates experience shear stress and reduces the peel stress acting on the adhesive joint. More images of the adhesive joint can be found in appendix 6-9.

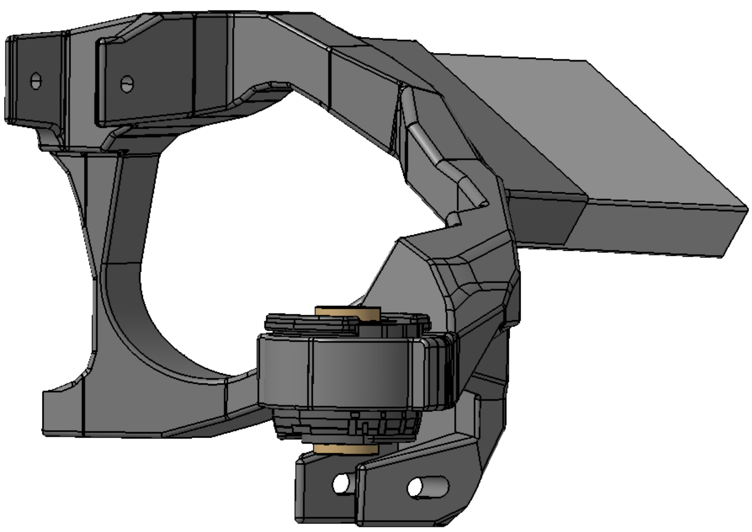


Figure 11, *Example of an adhesive joint*

4.1.4 Example of a Flow-drill screw joint and combined FDS-adhesive joint

The FDS joint is designed the same way as the adhesive joint, with a three-sided lap joint, but here flow-drill screws are used instead of adhesive. The three sides of the joint provide additional stiffness and strength when loaded in bending. There is a possibility of combining this joint with adhesive and creating a combined FDS and adhesive joint. Then the adhesive is applied, as described in chapter 4.4.3, and then the screws are attached. This would utilize the high strength and fatigue resistance of the adhesive joint but reinforce it against peel loads. Different views and angles of the joint can be found in appendix 10-12.

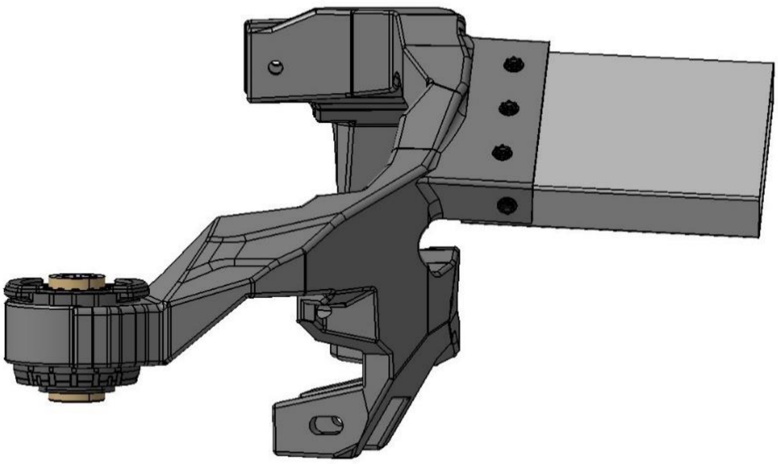


Figure 12, *Example of an FDS- and a combined FDS-adhesive joint*

4.2 Mechanical testing of welded joints

Since several die casting processes capable of producing weldable products has been identified, a test with welding of components from different casting processes was conducted.

One of the components that was welded was a part with fins in aluminium alloy ENAB 44300, produced by HPDC with vacuum assistance by a Fondarex Medio-P system in a 650ton cold chamber machine, with the thickness of 4,5mm. According to the manufacturer, the air pressure in the chamber should have been below 100mbar. The supplier of this component was Metallfabriken EVO AB.

Another of the welded components was a 2,5 mm thick rheocasted plates in aluminium alloy ENAB 42000 from Comptech i Skillingaryd AB. The plates were manufactured in a Bühler 600T cold chamber die casting machine.

Extruded aluminium flat bar, alloy EN-AW 6063-T6, thickness 3 and 4mm was the third material to be joined in these tests. The 3 mm piece was joined to the rheocasted detail and the 4 mm thick profile was joined to the vacuum assisted high pressure die casted part.

The components were cut into plates of suitable size and butt welded using a TIG- welding process. The welding was done by an experienced welder at a Volvo Cars facility to ensure the best conditions possible, and to get a professional opinion regarding the weldability of the material.

The plates were prepared by cleaning with a stainless wire brush and degreased using denatured alcohol. They were then chamfered to form a single v-butt joint with a 1 mm root face, the welding was done in one pass, achieving full penetration. The welding machine used was an ESAB 2200i AC/DC, set to AC. The amperage used in the tests varied since the welder used a foot pedal to control it as needed. The electrode used was a wolfram electrode and the welding filler metal used in these tests were $AlSi_{12}$ (4047).

After the welding was completed, three test pieces of each test material were then put through a tensile test in one of the research facilities at Volvo Cars at Torslanda.

4.2.1 Mechanical properties of base materials

Tensile tests were supposed to have been conducted on the base materials, however, problems occurred with the test equipment. In order to have a general idea of the mechanical strength of the joints, tensile strengths were then investigated on the base materials.

EN-AW 6063-T6 had an expected minimum ultimate tensile strength of 215MPa (Aalco Metals Ltd, 2019), ENAB 42000 (for permanent mould castings) had an expected minimum ultimate tensile strength of 170 MPa (Stena Alumninium) and ENAB 44300 (for pressure die castings) had an expected minimum ultimate tensile strength of 240MPa (Stena Aluminium).

4.2.2 Welding two pieces of EN-AW 6063-T6 (3mm)

In this test, two pieces of extruded EN-AW 6063-T6 with the thickness of 3mm were butt welded together. After welding, the part was cut into 20mm wide strips in order to fit the tensile testing device. Extruded 6063-T6 aluminium alloy is generally considered to be easily weldable, hence the 6063-material will be the reference in these tests.

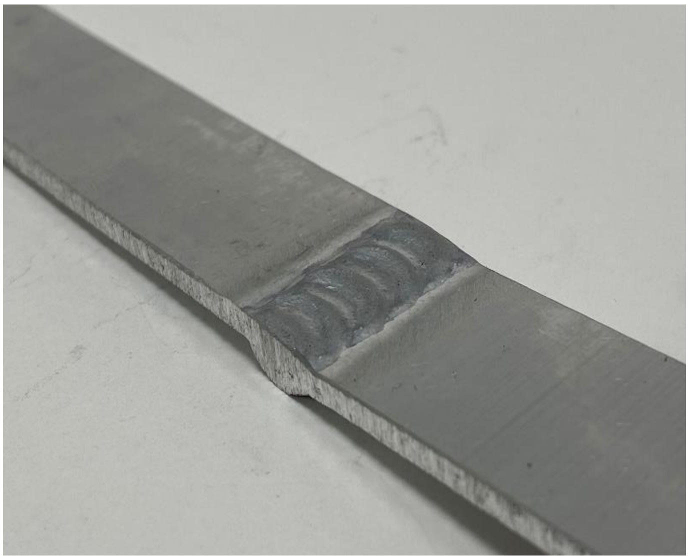


Figure 13, *Two pieces of EN-AW 6063-T6 (3mm) welded together*

4.2.2.1 Welder´s comment regarding the weldability of the materials

Welding these 6063-T6 pieces together was easy and the penetration was very good. Overall, an easy weld with no complication. No porosity was encountered when welded or when it was cut apart.

4.2.2.2 Tensile testing of the joint

The welded EN-AW 6063-T6 (3mm) to EN-AW 6063-T6 (3mm) pieces acted as a reference during the testing, and endured forces of 8,216kN, 8,131kN and 8,375kN before the breaking point of the sample. In this test the pieces plasticized at some distance from the weld.

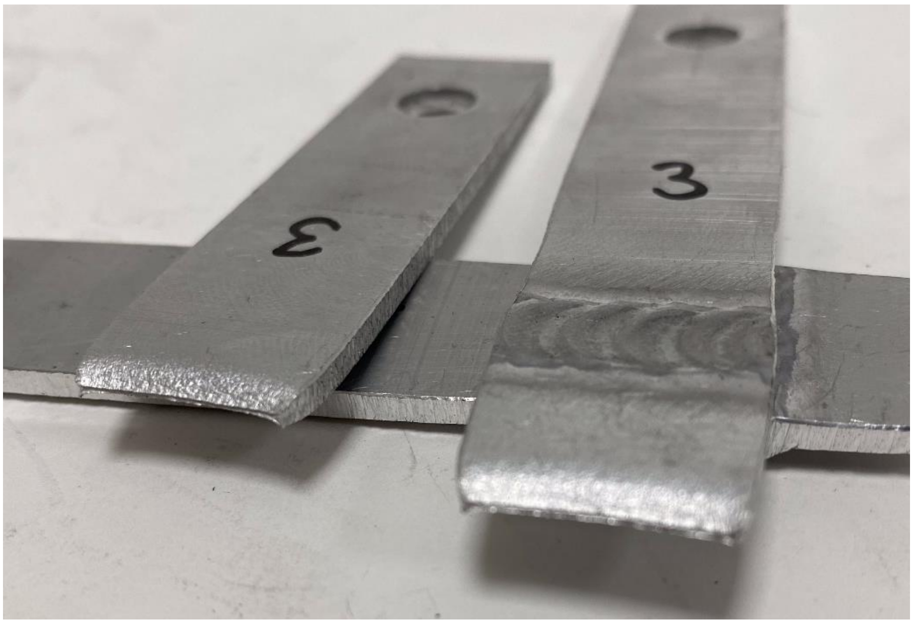


Figure 14, *Tensile testing of welded EN-AW 6063-T6 (3mm) to EN-AW 6063-T6 (3mm)*

4.2.3 Welding EN-AW 6063-T6 (3 mm) to ENAB 42000 (rheocasting)

In this test, a piece of extruded EN-AW 6063-T6 with the thickness of 3mm and rheocasted ENAB 42000 were butt welded together. After welding, the part was cut into 20mm wide strips in order to fit the tensile testing device.

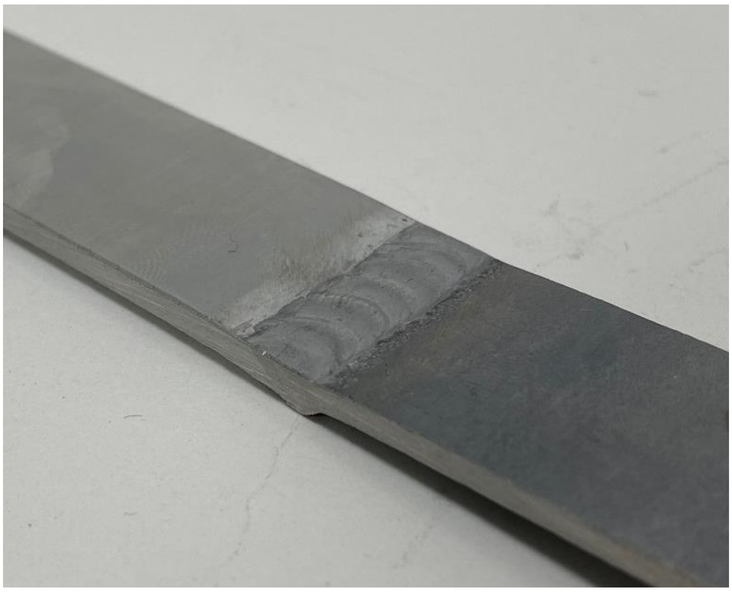


Figure 15, *EN-AW 6063-T6 (3 mm) welded to ENAB 42000 (rheocasting)*

4.2.3.1 Welder´s comment regarding the weldability of the materials

As expected, the rheocasted piece melted faster than the extruded piece due its lower melting point. To counteract this, the arc was aimed more towards the 6063-material than the rheocasted part. The weld went well and the bond felt strong with good penetration.

Some kind of impurity emerged when welding. The welder was not sure of exactly what it was, but it was a minimal amount and did not seem to cause any problems to the weld or disturb the process.

4.2.3.2 Tensile testing of the joint

The welded EN-AW 6063-T6 (3mm) to ENAB 42000 (rheocasted) pieces experienced forces of 8,829kN, 8,922kN and 8,871kN before the breaking point of the sample. In this test the extruded pieces (EN-AW 6063-T6) plasticized at some distance from the weld. The rheocasted part did not break.

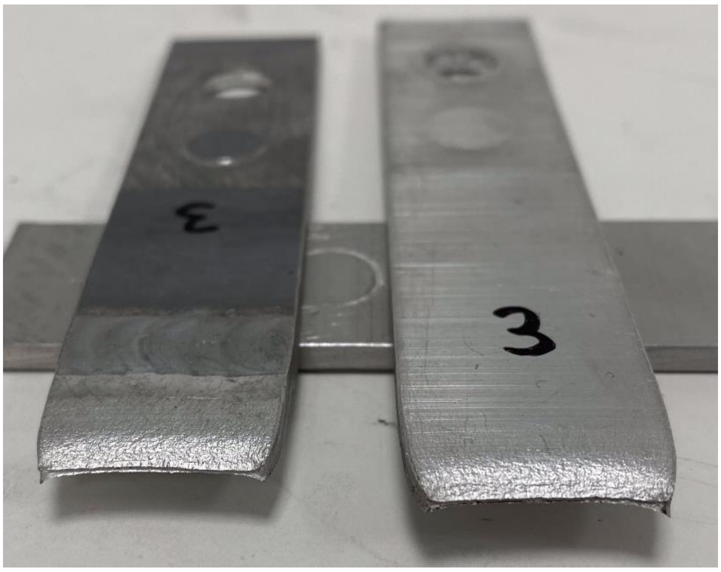


Figure 16, Tensile testing of *EN-AW 6063-T6 (3 mm) welded to ENAB 42000 (rheocasting)*

4.2.4 Welding EN-AW 6063-T6 (4 mm) to ENAB 44300 (V-HPDC)

In this test, two pieces of extruded EN-AW 6063-T6 with the thickness of 4mm and V-HPDC ENAB 44300 were butt welded together. The V-HPDC component did not allow for welding a large plate and cutting it into strips as was done for the other tests. Instead, several test pieces were made by welding 20mm wide parts.

Figure 17, *EN-AW 6063-T6 (4 mm) welded to ENAB 44300 (V-HPDC)*

4.2.4.1 Welder´s comment regarding the weldability of the materials

This material combination was not easily weldable. There was a lot of impurities in the V-HPDC material that emerged during welding, causing porosity. If multiple passes with the arc was made a better weld with less pores and contamination could possibly be obtained. In this test however, only one pass was made to simulate a production process. The arc was directed towards the 6063-material since the V-HPDC-material melts earlier, but no full penetration in the 6063-material was obtained.

4.2.4.2 Tensile testing of the joint

The welded EN-AW 6063-T6 (3mm) to ENAB 44300 (V-HPDC) pieces experienced forces of 7,782kN, 6,047kN and 8,168kN before the breaking point of the sample. In this test the area of the weld experienced the breaking point. The material in the bottom of the welded area seems to have been melted during welding but was not fused together well. There seems to be a lot of pores in the welded area.

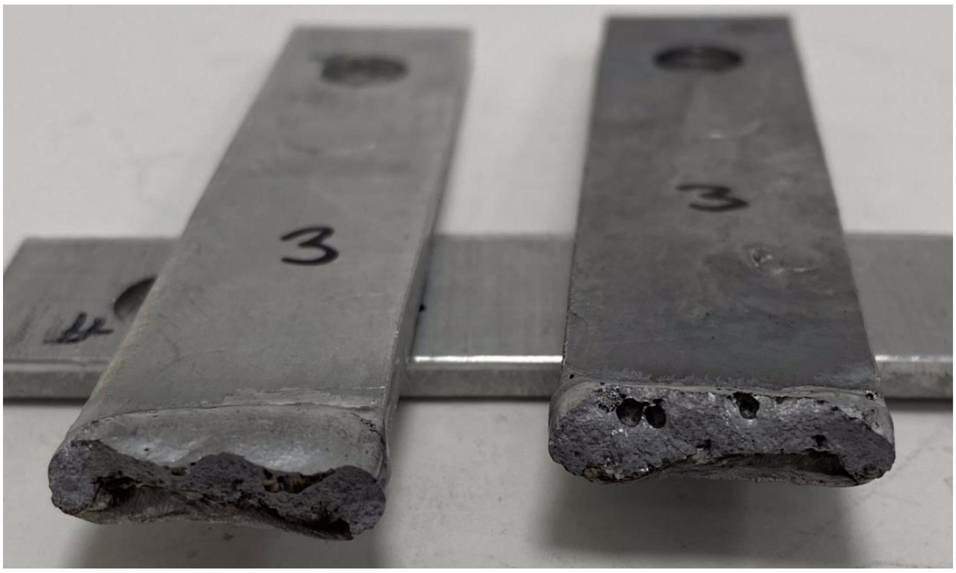


Figure 18, Tensile tested *EN-AW 6063-T6 (4 mm) welded to ENAB 44300 (V-HPDC)*

4.2.5 Welding two pieces of ENAB 44300 (V-HPDC)

In this test, two pieces of V-HPDC ENAB 44300 were butt welded together. The V-HPDC component did not allow for welding a large plate and cutting it into strips as was done for the other tests. Instead, several test pieces were made by welding 20mm wide parts.

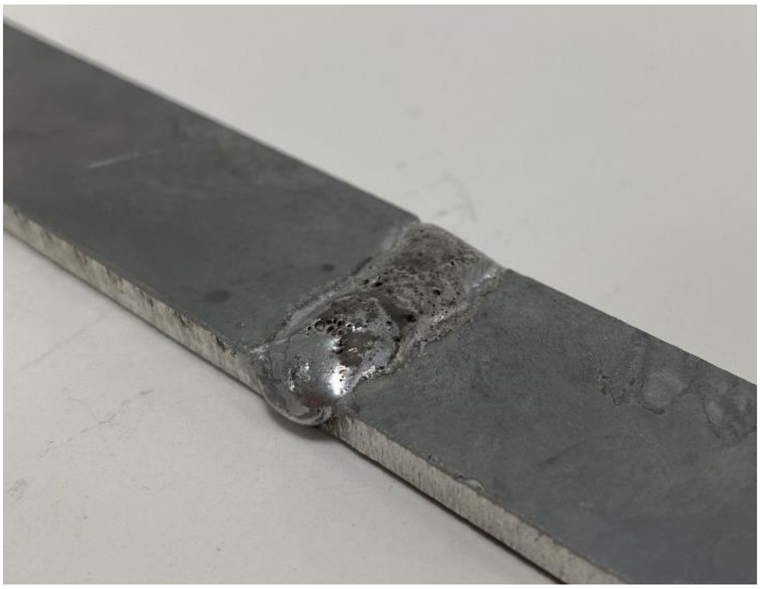


Figure 19, *Two pieces of ENAB 44300 (V-HPDC) welded together*

4.2.5.1 Welder´s comment regarding the weldability of the materials

Welding the V-HPDC-material together caused a lot of problems. There was a lot of pores and impurities in the weld and penetration was not great. Multiple passes with the arc could have made for a better weld with less pores and contamination. In this test however, only one pass was made to simulate a production process.

4.2.5.2 Tensile testing of the joint

The welded ENAB 44300 (V-HPDC) to ENAB 44300 (V-HPDC) pieces experienced forces of 5,984kN, 5,201kN and 6,142kN before the breaking point of the sample. In this test the area of the weld experienced the breaking point. The material in the bottom of the welded area seems to have been melted during welding but was not fused together well. There was a lot of pores in the welded area.

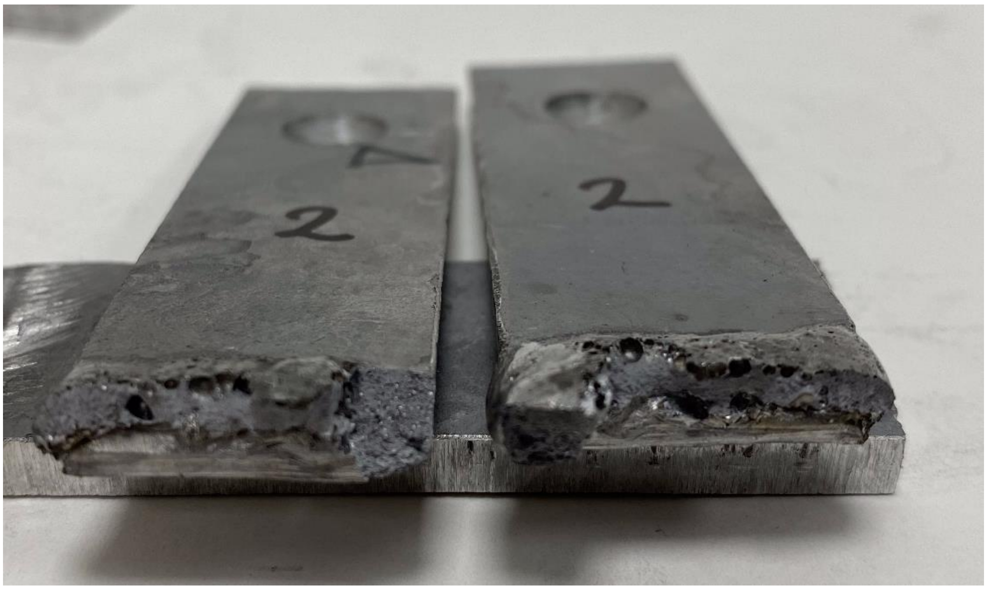


Figure 20, *Tensile testing of ENAB 44300 (V-HPDC) welded to ENAB 44300 (V-HPDC)*

4.2.6 Welding two pieces of ENAB 42000 (rheocasting)

In this test, two large plates of rheocasted ENAB 42000 were butt welded together. After welding, the part was cut into 20mm wide strips in order to fit the tensile testing device.

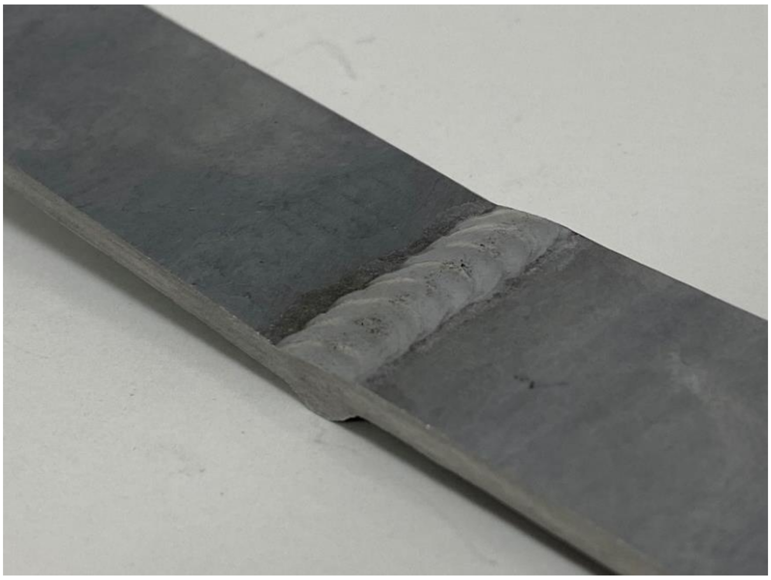


Figure 21, *Two pieces of ENAB 42000 (rheocasting) welded together*

4.2.6.1 Welder´s comment regarding the weldability of the materials

The welder experienced no problem welding the two rheocasted pieces together. The material melted easily and the bond was good. There is something of minimal size that emerges when welding, but it goes away and does not seem to cause any problems to the weld. It cannot be confirmed if it is pores, oxides or impurities from the environment, but it does not seem interfere with the weld´s performance.

4.2.6.2 Tensile testing of the joint

The welded ENAB 42000 (rheocasted) to ENAB 42000 (rheocasted) pieces experienced forces of 9,567kN, 8,716kN and 8,521kN before the breaking point of the sample. In this test the breaking point happened in close distance from the welded are.

Figure 22, *Tensile testing of ENAB 42000 (rheocasting) welded to ENAB 42000 (rheocasting)*

4.2.7 Compilation of tensile testing

A summary of the breaking force for the different test pieces was compiled and presented below. The average tensile strength was calculated using the average breaking force and the area were the fracture occurred.

Test material:	Breaking force:
EN-AW 6063-T6	
Standard minimum ultimate tensile strength:	**215MPa**
ENAB 44300 (for pressure die castings)	
Standard minimum ultimate tensile strength:	**240 MPa**
ENAB 42000 (for permanent mould castings)	
*Standard minimum ultimate tensile strength:	**170 MPa**
EN-AW 6063-T6 to EN-AW 6063-T6 (3mm):	
Test piece number: 2	8,216kN
Test piece number: 3	8,131kN
Test piece number: 4	8,375kN
Average value:	8,241kN
Average ultimate tensile strength:	**137,35MPa**
EN-AW 6063-T6 (3 mm) to ENAB 42000 (rheocasting):	
Test piece number: 1	8,829kN
Test piece number: 2	8,922kN
Test piece number: 3	8,871kN

Average value:	8,874kN
Average ultimate tensile strength:	**147,90MPa**
EN-AW 6063-T6 (4 mm) to ENAB 44300 (V-HPDC):	
Test piece number: 1	7,782kN
Test piece number: 2	6,047kN
Test piece number: 3	8,168kN
Average value:	7,332kN
**Average ultimate tensile strength:	**91,65MPa**
ENAB 44300 (V-HPDC) to ENAB 44300 (V-HPDC):	
Test piece number: 1	5,984kN
Test piece number: 2	5,201kN
Test piece number: 3	6,142kN
Average value:	5,776kN
***Average ultimate tensile strength:	**64,18MPa**
ENAB 42000 (rheocasting) to ENAB 42000 (rheocasting)	
Test piece number: 2	9,567kN
Test piece number: 3	8,716kN
Test piece number: 4	8,521kN
Average value:	8,934kN
Average ultimate tensile strength:	**178,68MPa**

Table 3, *Summary of the tensile testing*

* No record of minimum tensile strength for rheocasted ENAB 42000 could be found, only record of ENAB 42000 being casted in permanent moulds.

** The tensile strength was calculated using the area of the 4mm thick material. However, the actual stress level in the weld was likely higher since the materials did not fuse together along the entire thickness.

*** The tensile strength was calculated using the area of the V-HPDC test pieces and not in the fracture point, the weld, due to issues of calculating the welded area. The experienced stress in the weld is likely higher than in the material since the weld did not fuse the material together well.

5 Results and Discussion

5.1 The welding techniques

MIG, TIG and laser welding are all possible methods for joining HPDC aluminium parts and extrusions in a subframe. The wide variety of joint types makes welding an interesting method with greater freedom of design.

The main issue with welding is trapped gases in the castings, which create porosity in the welds and significantly reduces their strength. Different methods for degassing the melt during welding and significantly reduce porosity have been found. There is also the possibility of reducing the entrapped gasses in the castings to the point where they can be welded using standard equipment without any issues. Several methods supposedly capable of this, such as Vacuum-assisted High Pressure Die Casting, Pore free die casting and Semi-Solid casting have been identified. Apart from being weldable by standard equipment, these methods also provide better mechanical properties. The castings are also possible to heat treat, further improving their mechanical properties. This could be of great interest for further research and implementation for any joining method.

One downside to welding is that heat from the welding process creates a heat affected zone, (HAZ), with lower mechanical properties. This is likely why in the material testing, the EN-AW 6063-T6 material could only withstand stress levels of around 150MPa, even though the material before welding had a tensile strength of at least 215MPa. Depending on the materials and processes used, a post weld heat treatment may be utilised to restore the material properties.

If it is economical and practically possible due to the fit-up tolerances, laser welding is an interesting process since it provides a narrow heat affected zone, low heat distortion and a high welding speed. If not, MIG-welding would likely be the best alternative since it is faster than TIG-welding.

5.2 Adhesive bonding

To ensure good bonding between to pieces, surface pre-treatments are crucial. The removal of impurities and foreign molecules is imperative to maximize the molecular contact between the adhesive and substrate and in that way generate a good mechanical interlocking.

Some limitations that come with adhesive bonding is that there may be a need for expensive jigging if heat, high pressure and time are crucial for curing the adhesive. Using heat in the curing of the adhesive, may lead to an increase in the sensitivity to intergranular corrosion in some aluminium alloys, which needs to be accounted for when selecting an adhesive. Extensive pre-treatments of the bond area are required for good bonding strength, and the area needs to be kept clean during the gluing process. The impact and peel strength of the bond are more limiting than the tensile strength of the material and need to be accounted for when designing a joint. In order to obtain a good bond, only variants of lap or strapped joints are possible, since the shear strength of the bond is very good. It was discussed at Volvo Cars that a type of U-joint, as can be seen in chapter 4.1.3, is the only viable option since it counteracts the different peel stresses with shear stresses and that way makes for a stronger joint during crashes.

Advantages of adhesive bonding are that the load is evenly distributed over the whole bonding are and is not as concentrated as it is with mechanical joining and rivets. The bond has good fatigue characteristics and have a good resistance to sonic vibrations. There is also a possibility to join pieces of very different material thickness, which can be difficult with welding or mechanical joining. Another advantage of adhesive bonding is that there is no HAZ.

There are seven different types of adhesives and depending on the properties of the material, the viscosity may vary in order to obtain a good bonding strength. There are two classes of adhesive, thermosetting and thermoplastic resins, for a structural bond the best option is the thermosetting resins. This is due to the formation of more rigid and crosslinked structure in the adhesive that forms under the longer reaction. A type of thermosetting resin that is used in structural bonding between metals is epoxies. An epoxy that is developed to be a crash optimized structural adhesive is DuPont Betamate 1496, which has a tensile strength of 30 MPa and a shear strength of 24 MPa. This means that in order to obtain a bond with high strength properties, to compete with e.g., welding, rather large bonding areas need to be designed for.

5.3 Flow-Drill Screwdriving

Flow-Drill screws are plunged into a material, heating up the surface and forming a draught when penetrating the material. The threads keep the screw connected to the piece and securing it tightly once the draught cools down and shrinks. There is a possibility to join different types of material and for many aluminium alloys a thickness of 5mm can penetrated without the need of pre-made holes. The peel strength of the joint is better than of adhesive bonds, however the shear strength is less of the joint than of adhesive. The method is suitable for lap and strapped joints, as they need stacked materials. Some heat is generated during the process, however it is not enough to cause a heat affected zone like welding.

5.4 Hybrid joint of FDS and adhesive

A combination of FDS and adhesive can help remedy the issues regarding the poor behaviour in different load cases for the two individual methods. Peel strength and shear strength for the different methods have been proven to increase when making a hybrid joint. No different joint design is required since they both need stacked materials. An adhesive bond could be designed, and then flow-drill screws could be added.

6 Conclusions

In this study, different joining methods for joining high pressure die-casted and extruded aluminium has been investigated. The purpose was to find solutions for the joining of a non-ferrous subframe.

The conclusions of the study were:

- Welding the pieces together is possible, however, to obtain good joint qualities degassing during welding or controlling the porosity of the casting is needed. Possibly using other casting processes, like semi-solid casting, can help increase the weldability of the material and increase the bonding strength of the joint.
- Adhesive bonding is possible, however the joint needs to be designed to experience low peeling forces as it is the limiting factor of the bond.
- Riveting using flow-drill screwdriving (FDS) is possible to use, however the shear strength is limiting.
- Combining adhesive and FDS, creating a hybrid joint, is a possible joining method for the manufacturing of a subframe. The hybrid joint has better qualities than the individual joining methods.

Recommendations

1. Conduct tensile tests on laser welds, adhesive, flow-drill screws and combined joints, similar to what has been done for arc welds.
2. Make in-depth studies on the specific joining methods, not as general as in this report.
3. Conduct durability and fatigue testing on the different joints.
4. Research different aluminium alloys for application in casted and extruded components in order to obtain the optimal properties for intended joining method.

References

3M Company. (2012). *Choosing and Using a Structural Adhesive.*

Aalco Metals Ltd. (2019). *Aluminium Alloy 6063 - T6 Extrusions.*

Aluminum Extruders Council. (2022). *Subframes and engine cradles.* Retrieved from https://aec.org/page/subframes-engine-cradles

Ananda Rao, G., & Ramanaiah, N. (2019). *Dissimilar metals AISI 304 steel and AA 2219 aluminium alloy joining by friction welding method.* MLR Institute of Technology & A. U. College of Engineering, Department of Mechanical Engineering, Hyderabad & Visakhapatnam. Retrieved from https://www.sciencedirect.com/science/article/pii/S2214785319332717?ref=pdf_download&fr=RR-2&rr=79ffb44658791d22

Bayraktar, S., & Hekimoglu, A. P. (2021). Current technologies for aluminum castings and their machinability. In P. Davim, & K. Gupta, *Advanced Welding and Deforming* (Vol. Handbooks in Advanced Manufacturing). Rize, Turkey: Elsevier. Retrieved from https://www.sciencedirect.com/science/article/pii/B9780128220498000190

Berube, P. (2018). Weldability of Aluminum Alloys. In K. Anderson, J. Weritz, & G. Kaufman, *Aluminum Science and Technology* (Vol. 2A). ASM International.

Brown, Z., & Burton, P. (2007). *High Integrity Die Cast Aluminum Body Components.* Warrendale: SAE International.

Burt, V. (2018). Adhesive Bonding. In K. Anderson, J. Weritz, & G. Kaufman, *Aluminum Science and Technology* (Vol. 2A). Retrieved from https://dl-asminternational-org.proxy.lib.chalmers.se/handbooks/edited-volume/63/chapter/1395764/Adhesive-Bonding-1

Cornacchia, G., Dioni, D., Faccoli, M., Gislon, C., Solazzi, L., Panvini, A., & Cecchel, S. (2019). *Experimental and Numerical Study of an Automotive Component Produced with Innovative Ceramic Core in High Pressure Die Casting (HPDC).* University of Brescia, Department of Industrial and Mechanical Engineering, Brescia. Retrieved from https://mdpi-res.com/metals/metals-09-00217/article_deploy/metals-09-00217-v2.pdf?version=1551067823

Devienne, M. (2014). *Aluminum Brazing in Vacuum Furnaces.* Saint Quentin Fallavier: Industrial Heating. Retrieved from https://web.s.ebscohost.com/ehost/detail/detail?vid=0&sid=b7a19325-ec4b-4a05-9687-29db0c3e87c6%40redis&bdata=JkF1dGhUeXBlPXNzbyZhdXRodHlwZT1zc28mY3VzdGlkPXMzOTExOTc5JnNpdGU9ZWhvc3QtbGl2ZSZzY29wZT1zaXRl#AN=94187523&db=bsu

EJOT GmbH & Co. KG. (n.d.). *FDS® The Flow-Drill Screw for High-Strength Sheet Joints.* Retrieved from https://www.atf-inc.com/wp-content/uploads/2017/02/ATFFDS2017HighRes.pdf

Felinks, N., Overberg, T., Sarafraz, Y., Walther, F., & Biermann, D. (2021). *Adapted Process Strategies in Front Face Flow Drilling and Thread Forming of Lightweight Casting Materials.* TU Dortmund University, Department of Materials Test Engineering (WPT) & Institute of Machining Technology (ISF), Dortmund. Retrieved from https://www.sciencedirect.com/science/article/pii/S2212827121008751?via%3Dihub

Graf, A. (2021). Aluminum alloys for lightweight automotive structures. In P. Mallick, *Materials, Design and Manufacturing for Lightweight Vehicles.* Woodhead Publishing. Retrieved from https://www.sciencedirect.com/science/article/pii/B9780128187128000033

Hilgenberg, K., Rethmeier, M., & Fritzsche, A. (2020). Influence of welding parameters on electromagnetic supported degassing of die-casted and wrought aluminum. *Journal of Laser Applications*.

Huang, C., Chen, W., Sung, S., & Pan, J. (2018). *Mechanical Strength and Failure Mode of Flow Drill Screw Joints in Coach-Peel Specimens of Aluminum 6082-T6 Sheets of Different Thicknesses and Processing Conditions.* Michigan: SAE International.

IPG Photonics Corporation. (n.d.). *Metal Welding.* Retrieved from https://www.ipgphotonics.com/en/applications/materials-processing/metal-welding#[laser-welding-techniques]

Kang, H., Yoon, P., Lee, G., Park, J., Jung, B., Lee, J., . . . Choi, Y. (2020). *Evaluation of the gas porosity and mechanical properties of vacuum assisted pore-free die-cast Al-Si-Cu alloy.* Pusan National University, Korea Institute of Industrial Technology & Hyundai Motor Company, Department of Material Science and Engineering, Advanced Forming Process R&D Group & Light Metal Materials Development Team, Ulsan, Bulsan & Seoul. Retrieved from https://www.sciencedirect.com/science/article/pii/S0042207X20307776?ref=pdf_download&fr=RR-2&rr=7a7b4c08bb20abd4

Khurmi, R., & Gupta, J. (2005). *Textbook of Machine Design.* S Chand & Co Ltd.

Kridli, G., Freidman, P., & Boileau, J. (2021). Manufacturing processes for light alloys. In P. Mallick, *Materials, Design and Manufacturing for Lightweight Vehicles.* Woodhead Publisher. Retrieved from https://www.sciencedirect.com/science/article/pii/B9780128187128000070

Li, L., Jiang, H., Zhang, R., Luo, W., & Wu, X. (2022). Mechanical properties and failure behavior of flow-drilling screw-bonding joining of dissimilar aluminum alloys under dynamic tensile and fatigue loading. In C. R. Azevedo, *Engineering Failure Analysis* (Vol. 139). Retrieved from https://www.sciencedirect.com/science/article/pii/S1350630722004538

Mallick, P. (2020). Optimization of Structural Adhesive Joints. In K. Mittal, & S. Panigrahi, *Structural Adhesive Joints: Design, Analysis, and Testing.* John Wiley & Sons, Incorporated. Retrieved from https://ebookcentral.proquest.com/lib/chalmers/reader.action?docID=6270484

Mallick, P. (2021). Joining for lightweight vehicles. In P. Mallick, *Materials, Design and Manufacturing for Lightweight Vehicles.* Dearborn, MI, United States: Woodhead Publishing. Retrieved from https://www.sciencedirect.com/science/article/pii/B9780128187128000082

Mazumder, J., Webber, T., & Paura, R. (2011). Laser Beam Weld Design, Codes, and Quality Assessment. In T. Lienert, T. Siewert, S. Babu, & V. Acoff, *Welding Fundamentals and Processes* (Vol. 6A).

Messler Jr, R. (2004). *Joining of Materials and Structures.* Butterworth-Heinemann. Retrieved from https://www.sciencedirect.com/science/article/pii/B9780750677578500038

Midson, S., Pucella, G., & Côté, P. (2015). The benefits of Semi-Solid Casting for Aluminium Alloys. *Foundry Management & Technology*. Retrieved from https://content.ebscohost.com/ContentServer.asp?T=P&P=AN&K=156212374&S=R&D=bsu&EbscoContent=dGJyMNXb4kSep7M4y9fwOLCmsEuep69Ss664S7CWxWXS&ContentCustomer=dGJyMPGpt0mvr7VRuePfgeyx44Dt6fIA

Nunes, H., Emadinia, O., Vieira, M. F., & Reis, A. (2022). Low- and High-Pressure Casting Aluminum Alloys: A Review. In S. Rajendrachari, *Recent Advancements in Aluminum Alloys [Working Title]*. Retrieved from https://www.intechopen.com/online-first/85913

O'Brien, A., & Sinnes, K. (2015). *Welding Handbook* (9th Edition ed., Vols. Volume 5 - Materials and Applications). American Welding Society. Retrieved from https://app.knovel.com/hotlink/toc/id:kpWHVMAP13/welding-handbook-volume/welding-handbook-volume

Sigworth, G. (2018). Aluminum Casting Alloys and Casting Processes. In K. Anderson, J. Weirtz, & G. Kaufman, *Aluminum Science and Technology* (Vol. 2A). ASM International.

Stena Aluminium. (n.d.). *Aluminiumlegering EN AB-44300.* Retrieved from https://www.stenaaluminium.se/siteassets/document/product-sheets/nov2019/se/en-ab-44300.pdf

Stena Alumninium. (n.d.). *Aluminiumlegering EN AB-42000.* Retrieved from https://www.stenaaluminium.se/siteassets/document/product-sheets/nov2019/se/en-ab-42000.pdf

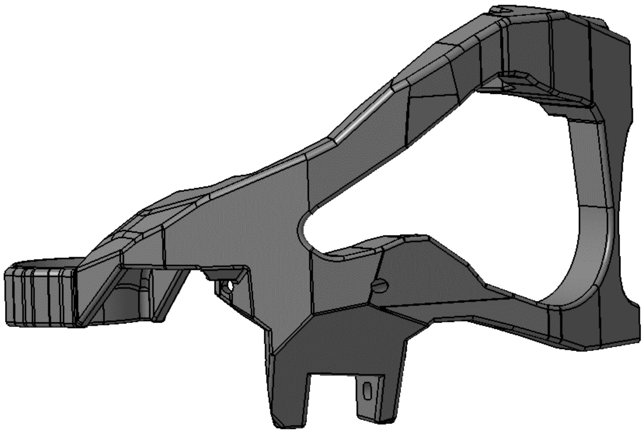
Thapliyal, S. (2021). Ultrasonic welding—a modern welding technology for metals and plastics. In P. Davim, & k. Gupta, *Advanced Welding and Deforming* (Vol. Handbooks in Advanced Manufacturing). Retrieved from https://www.sciencedirect.com/science/article/pii/B9780128220498000013#s0080

Uprapakam Ramakrishnan, M., & Mallick, P. (2022). *Behavior of Adhesive Lap Joints in Aluminum Tubes for Crashworthy Structures.* University of Michigan-Dearborn. SAE International.

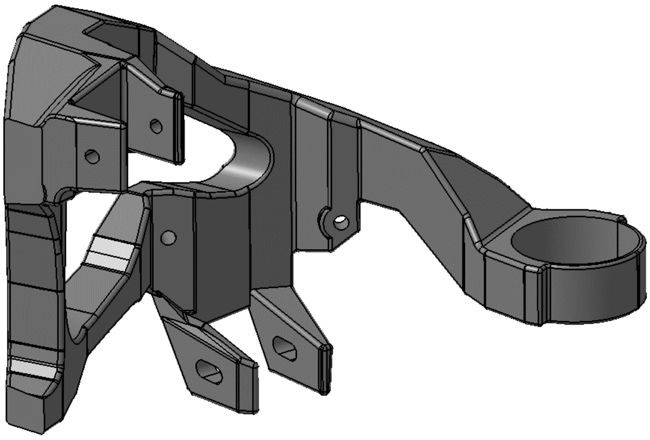
Wiesner, S., Rethmeier, M., & Wohlfart, H. (2005). MIG and laser welding of aluminium alloy pressure die cast parts with wrought profiles. *Welding International*. Retrieved from https://www.tandfonline.com/doi/pdf/10.1533/wint.2005.3380?needAccess=true

Ye, M., Wang, Z., Butt, H., Yang, M., Chen, H., Cui, . . . Lei, Y. (2022). *Enhancing the joint of dissimilar aluminum alloys through MIG welding approach assisted by ultrasonic frequency pulse.* Jiangsu University & Skolkovo Institute of Science and Technology, School of Material Science and Engineering, Zhenjiang & Moscow. Retrieved from https://www.sciencedirect.com/science/article/pii/S0167577X22016445?ref=pdf_download&fr=RR-2&rr=7a1158f4dcf6be49

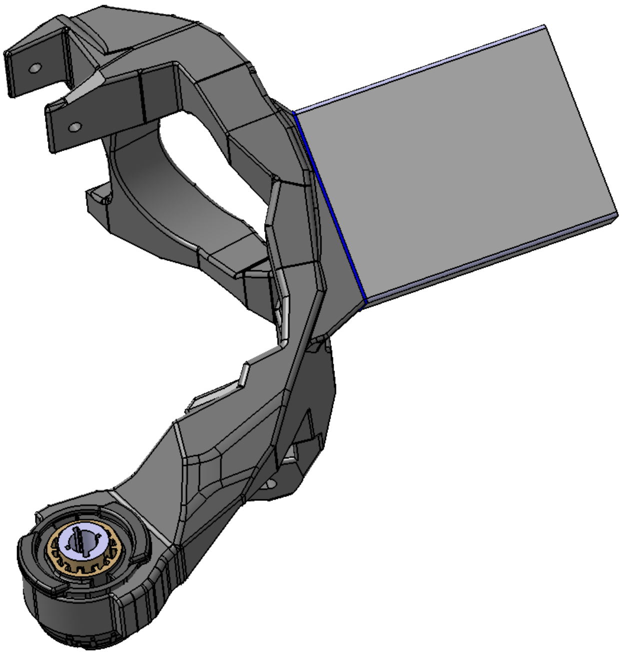
Appendix



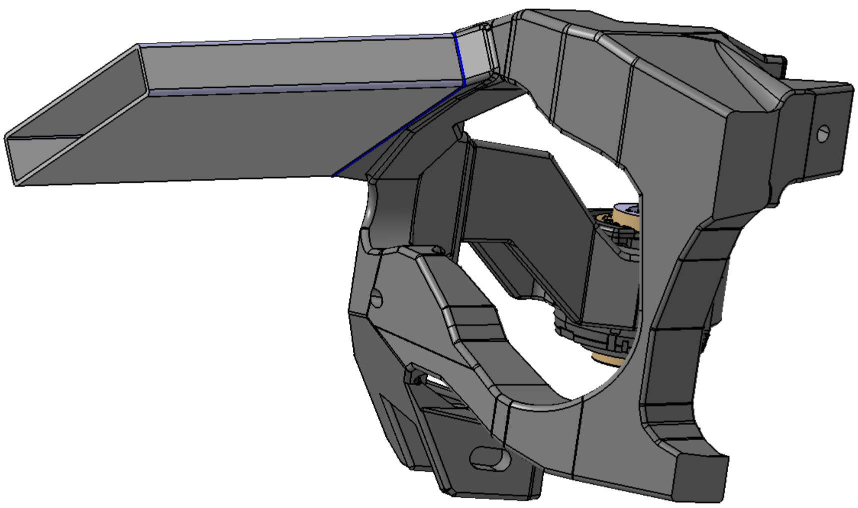
Appendix 1, *HPDC-converted section of the XC40 subframe 2*



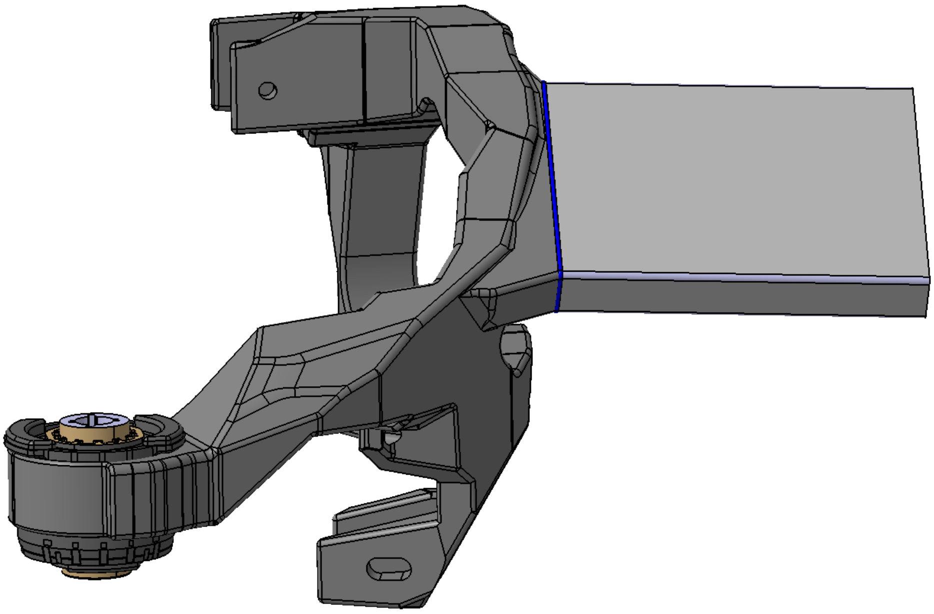
Appendix 2, *HPDC-converted section of the XC40 subframe 3*



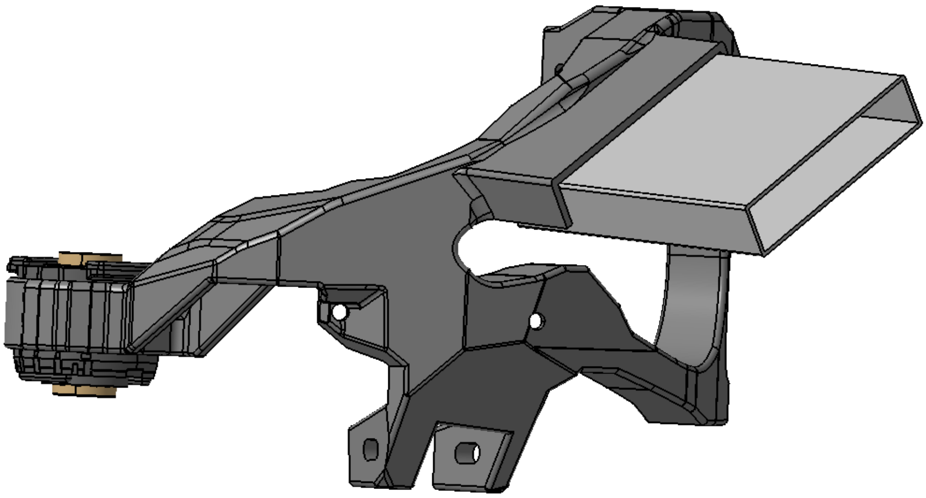
Appendix 3, *Example of a welded joint 2*



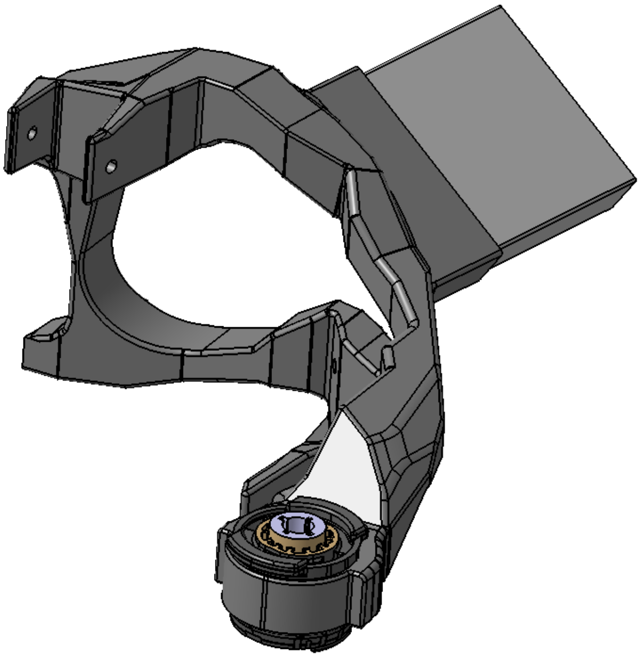
Appendix 4, *Example of a welded joint 3*



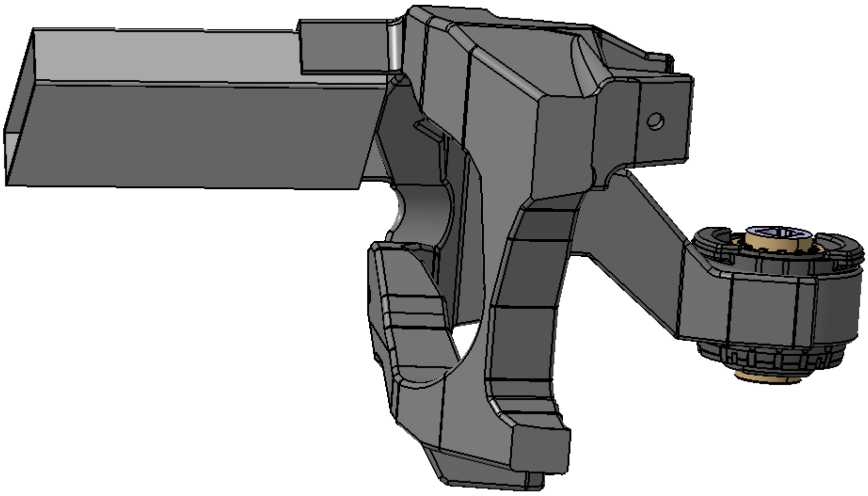
Appendix 5, *Example of a welded joint 4*



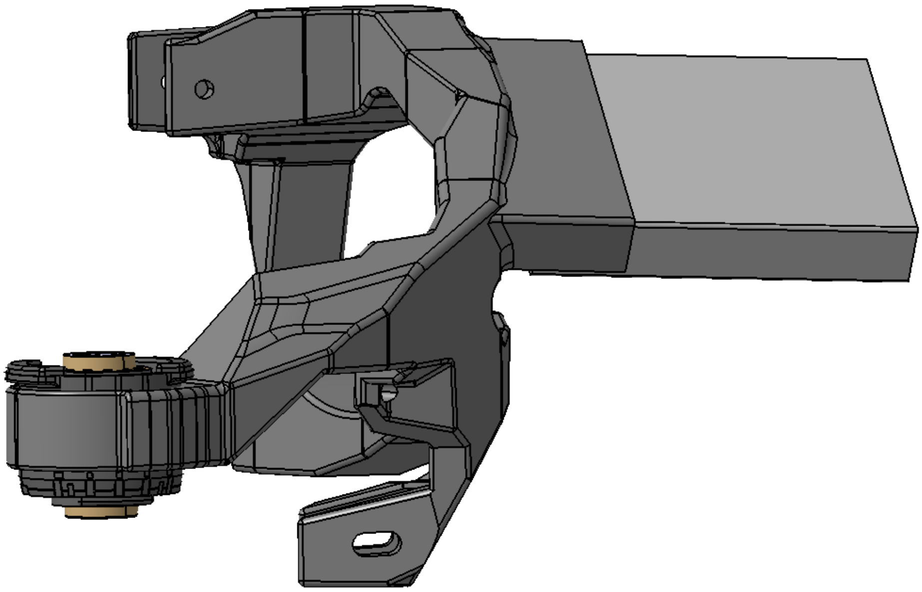
Appendix 6, *Example of an adhesive joint 2*



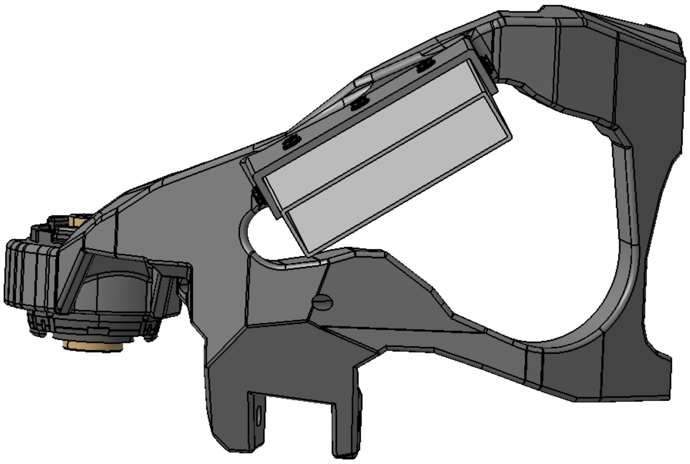
Appendix 7, *Example of an adhesive joint 3*



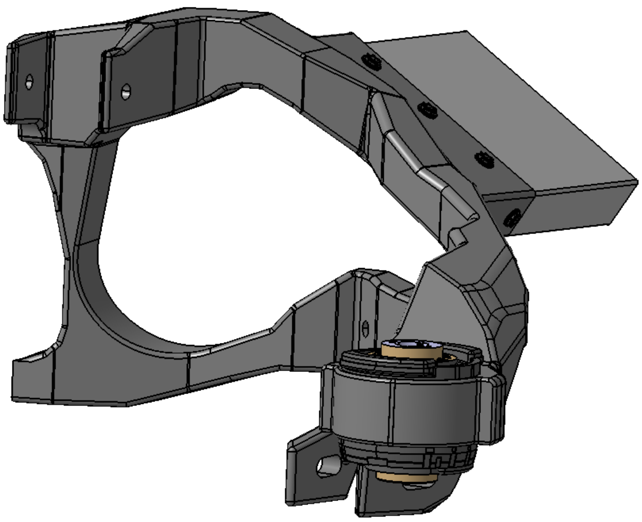
Appendix 8, *Example of an adhesive joint 4*



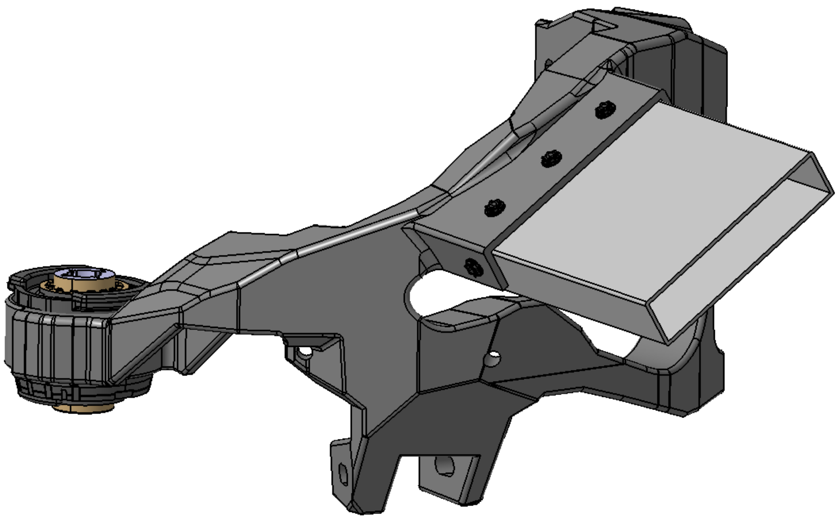
Appendix 9, *Example of an adhesive joint 5*



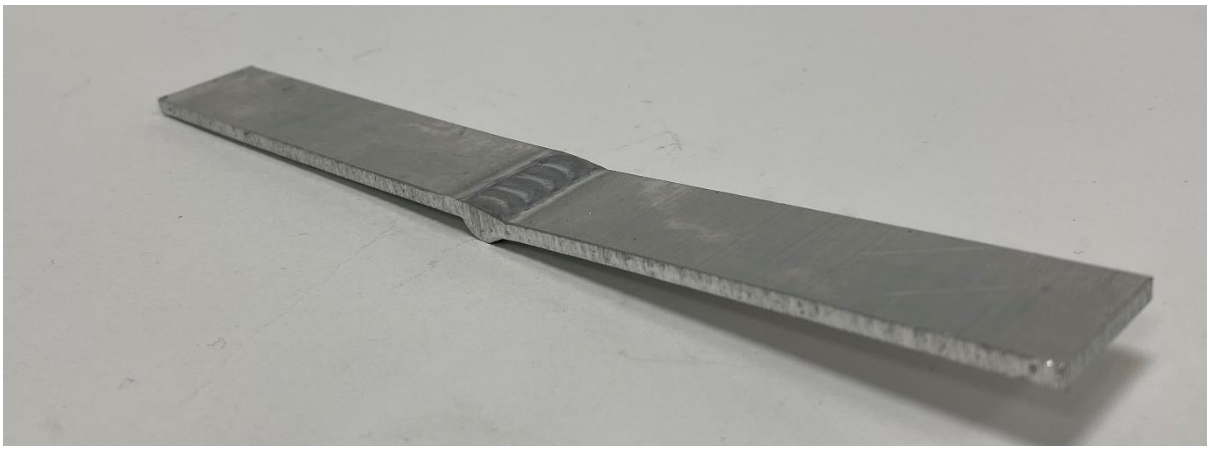
Appendix 10, *Example of a FDS- and a combined FDS-adhesive joint 2*



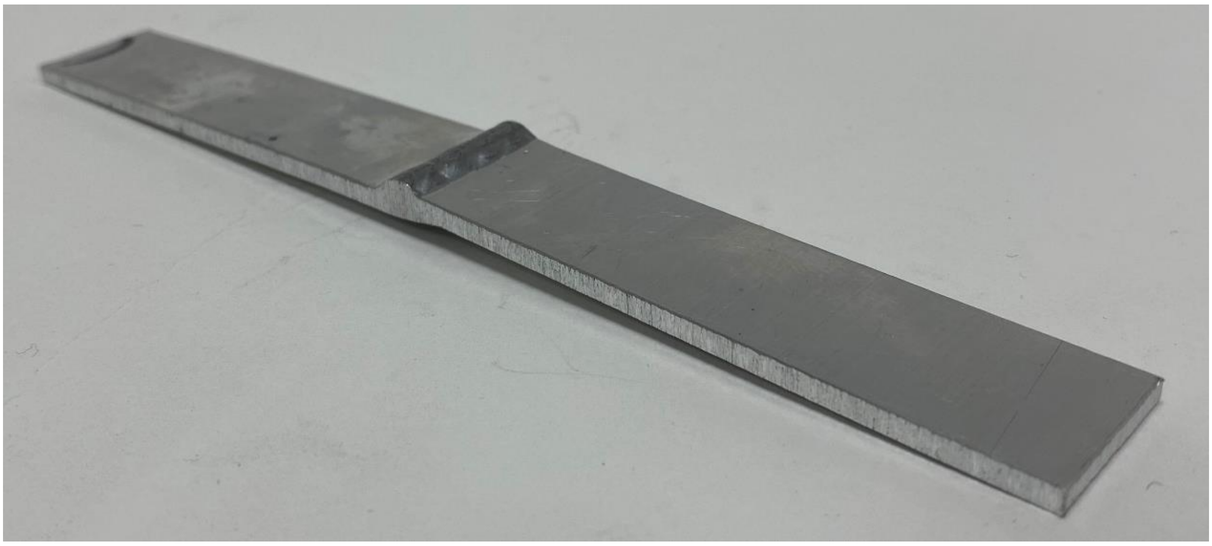
Appendix 11, *Example of a FDS- and a combined FDS-adhesive joint 3*



Appendix 12, *Example of a FDS- and a combined FDS-adhesive joint 4*



Appendix 13, *Two pieces of EN-AW 6063-T6 (3mm) welded together 2*



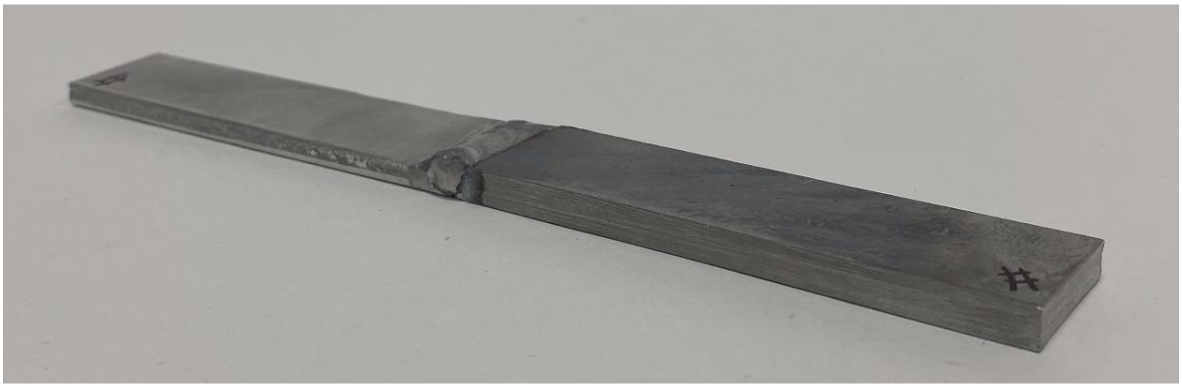
Appendix 14, *Two pieces of EN-AW 6063-T6 (3mm) welded together 3*

Appendix 15, *Tensile testing of welded EN-AW 6063-T6 (3mm) to EN-AW 6063-T6 (3mm) 2*

Appendix 16, *EN-AW 6063-T6 (3 mm) welded to ENAB 42000 (rheocasting) 2*

Appendix 17, *EN-AW 6063-T6 (3 mm) welded to ENAB 42000 (rheocasting) 3*

Appendix 18, Tensile testing of *EN-AW 6063-T6 (3 mm) welded to ENAB 42000 (rheocasting) 2*



Appendix 19, *EN-AW 6063-T6 (4 mm) welded to ENAB 44300 (V-HPDC) 2*

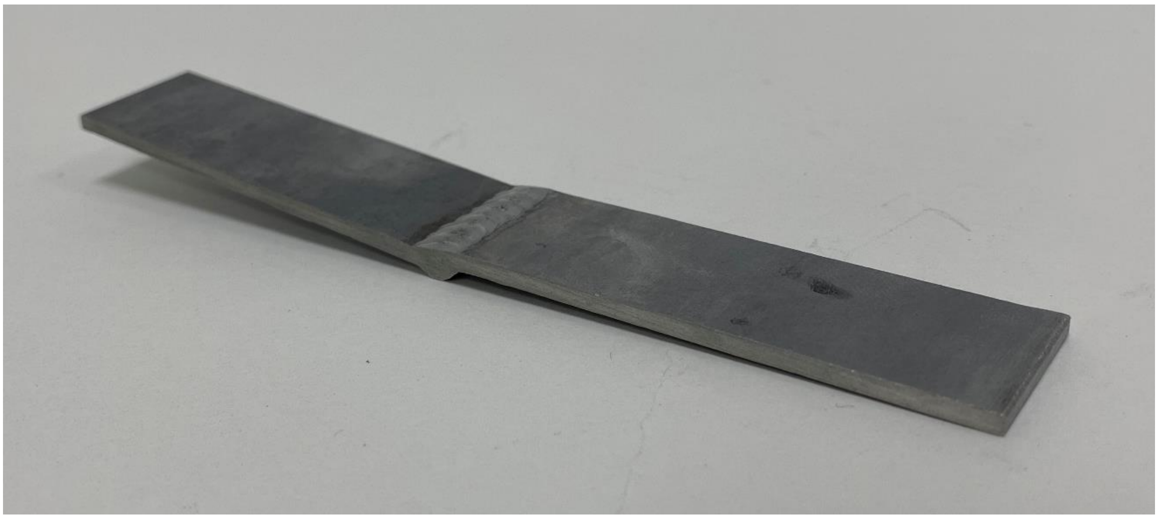
Appendix 20, *EN-AW 6063-T6 (4 mm) welded to ENAB 44300 (V-HPDC) 3*

Appendix 21, Tensile tested *EN-AW 6063-T6 (4 mm) welded to ENAB 44300 (V-HPDC) 2*

Appendix 22, *Two pieces of ENAB 44300 (V-HPDC) welded together 2*

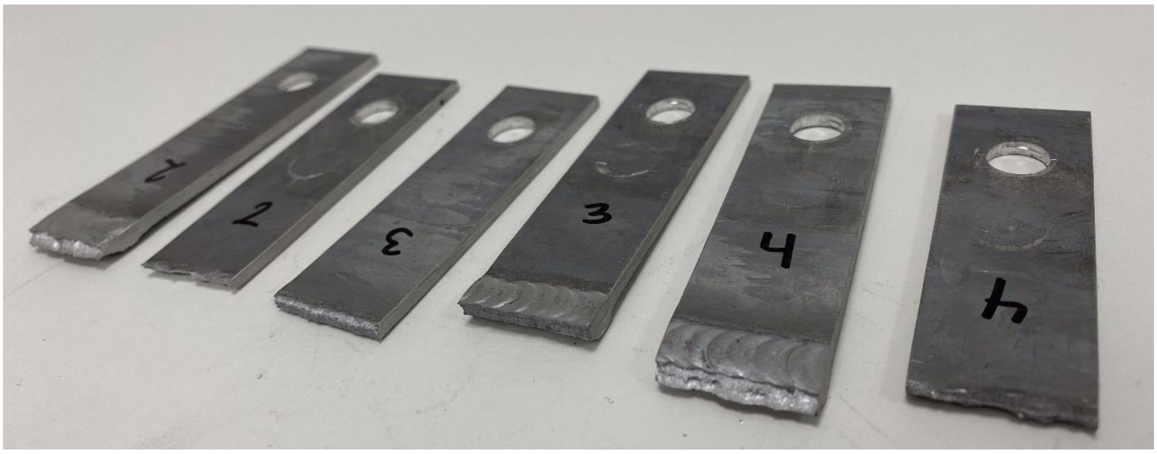
Appendix 23, *Two pieces of ENAB 44300 (V-HPDC) welded together3*

Appendix 24, *Tensile testing of ENAB 44300 (V-HPDC) welded to ENAB 44300 (V-HPDC) 2*



Appendix 25, *Two pieces of ENAB 42000 (rheocasting) welded together2*

Appendix 26, *Two pieces of ENAB 42000 (rheocasting) welded together 3*



Appendix 27, *Tensile testing of ENAB 42000 (rheocasting) welded to ENAB 42000 (rheocasting) 2*

DEPARTMENT OF MECHANICAL ENGINEERING
CHALMERS UNIVERISTY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY