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Development of Stationary Shoulder for Friction Stir Welding

Master’s thesis in the Masters Programme Product Development

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Gothenburg, Sweden 2014

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Abstract

Friction stir welding (FSW) is a welding technique where friction heat is used to forge metal components together. The method does not melt the material, instead the material is heated to forging temperature and mixed together. The possibility of welding different materials together and low residual stresses from heat in the weld pieces compared to other welding techniques are two examples of the advantages with FSW.

FSW is widely used for butt and lap welding of aluminium plates in industry today, ESAB being one of the large players in the market. ESAB has a patent of a technique allowing FSW welding of corner welds, using a stationary Shoulder. This technique is not used today in the industry and has not been tested by ESAB. This thesis describes the process of developing a prototype able to perform corner welds in 5mm aluminium plates with FSW using a stationary Shoulder. The prototype was built around ESABs lab machine that today is used for FSW butt and lap welds.

The chosen concept was a series of components that could be mounted on ESABs lab machine. The concept was able to fulfil all requirements from ESAB and manufacturing drawings were produced for all parts. Additional functionality of welding different material thicknesses was also added to the concept to prepare for further testing of the FSW process. Due to administrative delays at ESAB, a prototype could not be built in the given time line. ESAB was however pleased with the result and the prototype will be built and tested in the near future.

In addition to the prototype build, ESAB requested a concept for preheating the weld piece and welding wire prior to welding, as well as cooling the weld piece immediately after the welding. This additional task was a separated development process resulting in a separate concept, not including a prototype. The chosen concept uses a cartridge heater and a micro coil for heating the welding wire and the weld piece. The cooling is performed by water circulating thru the stationary Shoulder. The heating capability was tested in ANSYS thermal analysis. The concept was able to successfully heat the welding wire, the heating of the weld piece was however hard to assess and needs to be verified by physical testing. The cooling was also tested in ANSYS thermal simulation and the results showed a sufficient cooling of the weld piece.

Key words: FSW, friction stir welding, stationary Shoulder, ESAB

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Vocabulary list

ANSYS	Simulation software
Butt weld	Joining two work pieces that are in the same plane
Corner weld	In this thesis a weld of two work pieces which intersect in a 90 degree angle
Forging temperature	The temperature at which the metal becomes soft and formable, but below the melting temperature
FSW	Friction Stir Welding
Joint line	Interface between the work pieces that are going to be welded
Lap weld	Joining two work pieces that overlap each other
Leveller	Straightens the coiled welding wire
SolidWorks	Computer aided design software
Spindle axis	The rotating axis of the lab machine
Tee weld	Joining two work pieces in a 90 degree angel with two welds.
TIG	Tungsten Inert Gas
Weldon interface	Commercially available fastening system for work tools
Weld piece	The work piece that the welding is performed on
Weld zone	The area where the weld piece is at forging temperature
Wire feeder	Electric engine that feeds the welding wire

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1 Introduction

1.1 Background

Friction Stir Welding (FSW) is based on the principle of obtaining sufficient high temperatures to forge two metal components, using a rotating tool that moves along a joint line. The metal is not melted as in the majority of welding operations. Instead in FSW, the metal is heated to forging temperature, making the metal soft. This has many advantages, the biggest ones being low residual stress from the heat and the ability to weld different materials. Furthermore, FSW has been shown to produce high strength joints without inclusions or impurities. This welding technique is most common in aluminium, mainly since aluminium is hard to weld with common operations. Welding steel plates is also possible but is not commonly used due to the long welding time and high tool wear.

The two main components in FSW are the Probe and the Shoulder, shown in figure 1. The Probe is a rotating tool with the main functions of penetrating the material, generating frictional heat and stirring the heated material. The Probe has a threaded surface that pushes the heated material towards the weld. The Shoulder has the main function sealing the heated material inside the weld zone and creating frictional heat. The Shoulder also has the function of forming the finished weld. In normal FSW the Shoulder is a part of the same tool as the Probe and thus rotating.

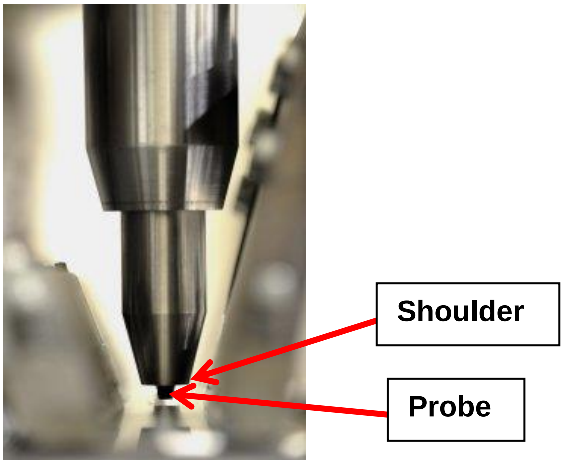


Figure 1: The Shoulder and the Probe of a FSW tool (ESAB, 2014)

Today FSW is primarily used for butt and lap welding. This is because no extra material is needed to forge the material together. When welding corner welds additional material is often added to form a fillet that makes the structure more rigid. This is hard to achieve when welding with current FSW methods. The reason why it is hard is because in today's FSW method, the Probe and the Shoulder rotate together, making it impossible to create a fillet and hard to feed welding wire into the weld. This thesis is about creating a non-rotating stationary Shoulder to enable a FSW machine to create corner welds. Being able to weld corner welds would open up market segments to create complex aluminium profiles. This could possibly compete with the process of extruding or TIG welding aluminium profiles.

The project will be performed for ESAB in Laxå which has a large manufacturing and development of welding equipment. Today ESAB develops, manufactures and sells FSW machines and tools for butt and lap welding.

ESAB has in its patent "Retractable Pin Shoulder" a demand that describes welding with a stationary Shoulder on FSW (Larsson, 1998). This has been tested at a company with ESAB as a sponsor. Due to confidentiality this company cannot be named in this report and will from now on be referred to as Company X. ESAB has obtained the result and the drawings of the studied device. Company X did not have wire feeding in their construction. Instead, to provide the extra welding material a welding wire was placed in the corner of the weld pieces before the welding operation. The welding wire was then run over by the Shoulder and mixed into the weld by the Probe. While this worked, it is not ideal since the amount of filler material cannot be regulated to different material thicknesses. It also poses problems with the Shoulder design and the operation of getting the welding wire to the rotating Probe without losing sealing capability. Another issue with Company X's solution is that the stationary Shoulder and the Probe were directly connected, meaning that the Shoulder pressed down on the weld piece with the same force as the Probe. This poses restrictions in the amount of force that can be used on the Probe, and therefore also restrictions in material selection and material thickness.

1.2 Objectives

ESAB wants a construction that allows them to weld corner welds with their current FSW lab machine with the principle tested by Company X. Having obtained Company X's results, ESAB wants to optimize Company X's solution by making a number of changes. These changes include direct feeding of welding wire to the Probe and a construction that enables independent movement and force between the Probe and the Shoulder. This would enable ESAB to use the same Probe and Shoulder to weld different aluminium alloys. It would also increase the welding speed according to ESAB. Constructing this is considered to be part 1 of the objective.

In addition ESAB would want a device that enables preheating of the work piece and the welding wire. This will enable higher welding speeds since the forging temperature will be reached faster. ESAB also wants cooling of the weld piece after the welding; this would enhance mechanical properties of the weld piece by reducing residual stresses. Constructing this is considered to be part 2 of the objective.

Both part 1 and part 2 of the objective are performed so that ESAB's can test the FSW corner weld principle and present it to possible customers. If successful, further development will be performed. Because of this, no changes will be made to the current lab machine. The solution will work as a complement to the lab machine, to be able to test and demonstrate the potential of corner weld FSW with wire feeding.

1.3 Deliverables

Since the project is divided into two parts there are also different deliverables for the objectives. The timeline of the project, objective 1 being constructed first, poses different prerequisites on the possibilities to build prototypes and perform tests. Therefore the deliverables of objective 2 are going to be more theoretical. The full deliverables of both objectives are stated in the following subchapters.

1.3.1 Part 1

- Approved concept, able to fulfil objectives and implementation on ESAB's current lab machine
- Detailed concept, with CAD models and necessary analysis performed
- Manufacturing drawings, to be able to outsource the manufacturing of a working prototype
- Test results, making weld tests using the prototype to identify enhancement possibilities

1.3.2 Part 2

- Approved concept, able to fulfil objectives and implement on ESAB's lab machine
- Detailed concept, with CAD models of parts and necessary analysis
- Manufacturing drawings, for possible future prototype

1.4 Scope

- The scope is limited to a prototype that fits the current lab machine. No regard to future production is to be considered.
- No changes of the lab machine will be made, only available mounting points will be used
- The wire feeder and leveller will not be constructed, only modified and fitted to the prototype
- The concept is limited to welding corner welds
- The concept will be limited to welding 5mm thick AL5XXX and AL6XXX plate alloys
- The Shoulder should be limited to creating a 5mm fillet, however replacement of Shoulder should be possible to enable test with other fillet dimensions
- The interface between constructed tool and the lab machine spindle axis will use current 50mm Weldon interface
- The Shoulder pressure should use the current 180MPa hydraulic pressure available at the lab machine
- The prototype of the part 1 objective will be constructed by a third party
- The cooling of the weld piece will use the current water tank and pump available on the lab machine

1.5 Method

In the beginning of the project a lot of literature, drawing and analysis studying will be performed. This together with studying of ESAB's lab machine will give a deeper knowledge of the FSW process and the basis for future work.

Part 1 will then be started. It will be performed with a product development method, including concept generation, detailed development and testing.

Part 2 will be started when the prototype for objective 1 is being manufactured. The process will be similar to the one used for objective 1, but excluding prototyping and testing.

The project will be performed both on distance and at ESAB in Laxå. There will be both regular meetings with responsible actors on site in Laxå and distance meetings from Gothenburg. The testing of the prototype will be performed at ESAB in Laxå. All 3D modelling will be conducted in SolidWorks and all FEM simulations will be conducted in ANSYS.

2 Thesis outline

The thesis starts with FSW theory in section 3; this includes normal FSW theory followed by ESAB's current position regarding FSW and the thermal theory specific for the part 2 development. The general preconditions affecting both the part 1 and the part 2 of the project are then presented in section 4.

The development and concept presentation of part 1 and part 2 are separated in the report; this is done in coherence with the work procedure of the project and to avoid confusing the reader. The part 1 development is found in sections 5-7.

The development of part 1 and 2 is divided into concept generation, concept selection and final concept. A separate precondition chapter is included prior to the part 2 development in section 8. The part 2 development, with concept generation, concept selection and final concept can be found in sections 9-11.

The thesis continues with a discussion regarding the future perspective of FSW in section 12 and a conclusion in section 13. All analyses, scripts, drawings and calculations not found in the thesis are presented in the appendices.

3 Theory

This section describes the theory behind the project. First the general theory for normal FSW is presented followed by the theory behind FSW stationary Shoulder. In the last sub section the thermal theory used for Part 2 is described.

3.1 Normal FSW

When creating a weld with FSW, the Probe is positioned over the joint line where the weld is going to start. The Probe starts to rotate and is then moved down with help of a hydraulic cylinder. The Probe penetrates the material using high pressure. The friction between the rotating Probe and Shoulder against the weld piece creates heat. When the weld piece reaches forging temperature the Probe and the Shoulder starts to move along the joint line, creating a weld. In addition to creating frictional heat the Probe also mixes the materials together, and by that joining them together. The Shoulder slides on the surface of the weld piece, preventing the heated material to escape outside the weld. If no Shoulder would be used the heated material would be forced out from the weld. This is due to the high pressure generated by the down force of the Probe and the fact that the Probe forces the material down with the help of its threads. When the weld is finished the Probe is lifted up while still rotating. The welding process is shown in figure 2. A risk with normal FSW welding is that a meltdown can occur. A meltdown is when the Shoulder sinks into the material due to the high temperature at the weld piece surface. In stationary Shoulder FSW this is not a problem, this is since the Shoulder slides over a relatively cold surface and does not create friction heat by rotating (Backer, 2014).

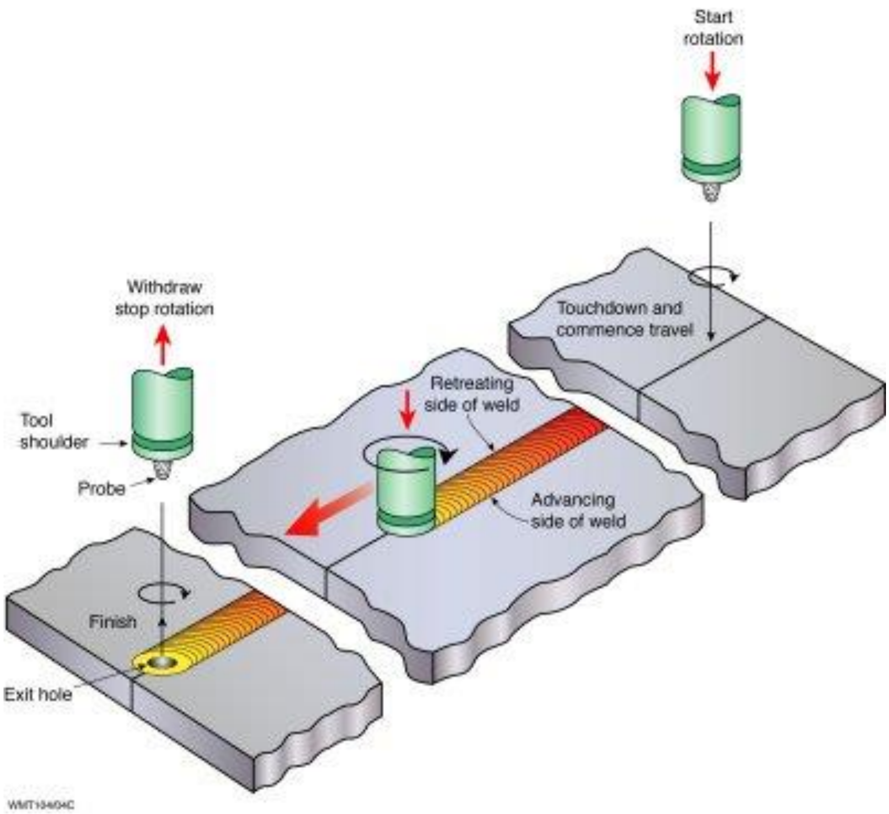


Figure 2: The picture sequence shows the welding procedure for normal FSW (ESAB, 2014)

3.2 Stationary Shoulder FSW

When welding corner welds, the weld needs to have a fillet in order for the weld piece to achieve high enough rigidity. To be able to create this fillet additional material needs to be supplied into the weld. The additional material then needs to be mixed with the weld and shaped into a fillet. Because of the 90 degree angle of the weld piece and the shaping of the fillet it is not possible to have a rotating Shoulder. This is not possible since a rotational symmetric Shoulder cannot create a fillet and at the same seal the weld, preventing heated material to escape the weld. A rotating Shoulder also makes it very hard to feed a wire directly to the Probe. This is why a stationary Shoulder is needed to be able to create a corner weld. When trying to create a corner weld with normal FSW without wire feeding the Shoulder will cut into the weld piece creating a non-rigid weld as seen in figure 3.

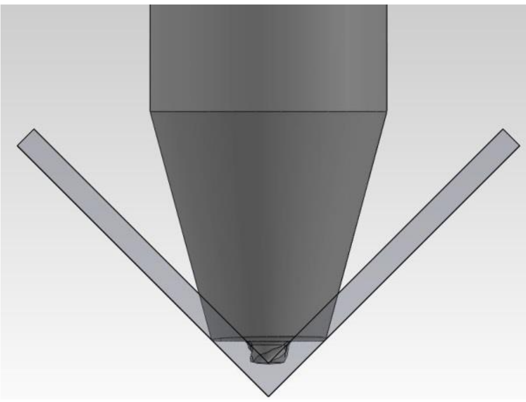


Figure 3: The picture shows how the Shoulder would cut into the weld piece when using a normal FSW tool trying to weld a corner weld

3.3 Company X stationary Shoulder FSW

Company X has successfully tested creating corner welds in aluminium with a stationary Shoulder. Company X had the Shoulder and the Probe connected to the same hydraulic system, this meant that the Shoulder and the Probe had the same down force on the weld piece. To supply the extra material, a wire was placed in the corner of the weld. This was then run over during the welding process.

Company X has Probe and Shoulder designs developed for welding aluminium with 1.6, 4, 8 and 12mm thickness.

3.4 ESAB stationary Shoulder FSW

Unlike Company X, ESAB does not want the Probe and the Shoulder connected to the same hydraulic system. This is because the Probe needs a higher down force than the Shoulder, due to the fact that the Shoulder needs to seal against the weld piece while the Probe has the function of penetrating the weld piece. To be able to use lower down force, Company X used Probes with different conical shape to weld different alloys. ESAB's solution for this is to have separated down force for the Probe and the Shoulder. Having the Shoulder and Probe separated also means that higher down forces can be used for the Probe, meaning that higher welding speeds can be achieved. Having separate linear steering of the Shoulder and Probe also means that the Shoulder can put pressure on the weld piece before the Probe penetrates the material surface. This prevents heated material from escaping the weld in the beginning of the welding procedure, resulting in a better weld.

The requested procedure from ESAB of creating a corner weld with a stationary Shoulder is performed in five steps. First the Shoulder is lowered down, putting pressure on the weld piece. The Probe is then, as in normal FSW, lowered down while rotating until penetrating the weld piece. When the weld piece reaches forging temperature the Shoulder and Probe move synchronized along the weld. As in normal FSW the Shoulder prevents heated material to escape outside the weld while gliding on the surface of the weld piece. The stationary Shoulder also forms the weld into a fillet. During the welding process a welding wire is fed above the weld directly to the Probe, thus allowing a fillet to be created. When the weld is finished the Probe is lifted up while still rotating, the Shoulder is still kept with pressure on the weld piece. The Shoulder is then lifted up from the weld piece after the Probe. The welding process described is shown in figure 4.

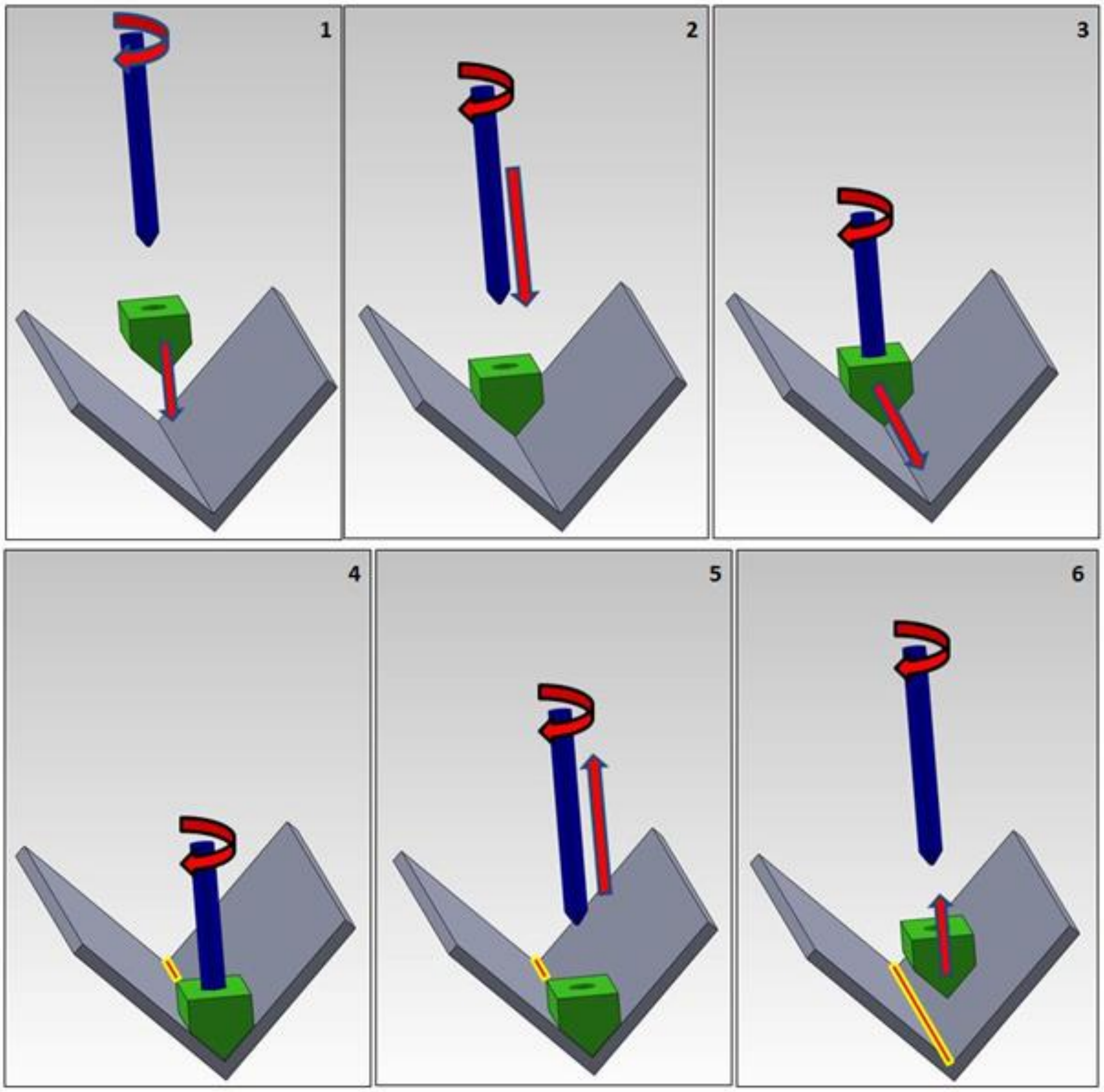


Figure 4: The picture sequence shows the welding procedure for FSW with stationary Shoulder. 1) The Shoulder is lowered down to the weld piece, keeping constant pressure on it. 2) The Probe is lowered down thru the Shoulder while rotating. 3) When the weld piece reaches forging temperature the Probe and Shoulder starts to move along the joint line. 4), 5) When the weld is finished the Probe is raised up while still rotating. 6) The Shoulder is moved up and the welding operation is finished.

3.5 Thermal theory

In the part 2 development a large focus was put on heat removal and heat supply of the weld piece. There are basically three different modes of heat transfer; conduction, convection and radiation. Conduction and convection had a large importance on the modelling of the cooling and heating concepts and will be shortly described in this chapter. The thermal inertia of the involved components was also important for the modelling. This is because the system is time dependent and the heat transfer will change with the amount of heat absorption of the involved components. The thermal inertia is usually referred to as specific heat, which will also be described in this chapter.

3.5.1 Conduction

Conduction is the transfer of energy from particles with high energy level to particles with low energy level. (Yunus A. Cengel, 2007) In gases and liquids the energy transfer is caused by collisions of adjacent molecules. In solids the conduction is a result of vibration of the grid of molecules and the transport of free electrons. The conduction is usually described by Fourier's law, which indicates that the rate of heat conduction in a specified direction is proportional to the temperature gradient in that direction.

Conduction is the mode of energy transfer in adjacent metals, so the primary energy transfer in the Shoulder and from the Shoulder to the weld piece is conduction. This was relevant in both the heating and the cooling applications.

3.5.2 Convection

Convection is a combination of conduction and fluid motion and is present between a solid body and the adjacent gas or fluid. (Yunus A. Cengel, 2007) The rate of heat transfer is greater with a higher fluid motion and with the case of no fluid motion the energy transfer will be purely conduction.

There are two types of convection; natural- and forced convection. Natural convection is when the fluid motion is a result of buoyancy forces due to density differences in the fluid or gas. Forced convection is when the fluid motion is triggered by an external force, like a fan or a pump.

The rate of cooling for a surface in contact with a fluid or gas is described by Newton's law of cooling (see equation 1). Since water was set to be used as coolant, forced convection is the primary mode of energy transfer in the cooling concept. The convection heat transfer coefficient (h) is an experimentally determined constant. In forced convection the heat transfer coefficient is dependent on several dimensionless parameters as well as the viscosity, the speed, the geometry of the flowing interface, the density, the thermal conductivity and the specific heat of the fluid or gas.

$$\dot{Q} = hA(T_s - T_f) \tag{1}$$

$$\dot{Q} = thermal\ convection\ [W]$$
$$h = heat\ transfer\ coefficient\ [\frac{W}{m^2K}]$$
$$A = area\ of\ surface\ [m^2]$$
$$T_s = surface\ temperature\ [K]$$
$$T_f = fluid\ temperature\ [K]$$

A heat transfer process where the fluid has a change of phase is also considered to be convection. This could for example be a process where the fluid vaporizes or condensates. A convention process that includes a phase change has a larger heat transfer coefficient than a constant phase heat transfer.

3.5.3 Specific heat

Specific heat is defined as the amount of energy required to raise the temperature of a unit of mass by one degree. (Yunus A. Cengel, 2007) There are two different kinds of specific heat; specific heat at constant volume (C_v) and specific heat at constant pressure (C_p). C_p is always larger than C_v since the energy required for the expansion work is added.

4 General preconditions

In the general preconditions both demands from ESAB and restrictions from the properties of the lab machine are included. Because the finished prototype was going to be mounted on ESAB's current FSW lab machine, a number of preconditions for the interfaces had to be considered. For the interface of the prototype on the lab machine a flat surface on the front of the lab machine was allowed to be used. This surface has eight holes that allowed mounting of the prototype. The interface to the spindle axis was given to be a 50mm Weldon interface. The Weldon interface will translate the momentum and rotational movement from the spindle axis to the Probe. A cooling pipe with 8mm diameter goes through the spindle axis and continues 70mm outside the spindle axis edge. This cooling pipe is not movable and needed to be incorporated in the concept. The flat mounting interface, the spindle axis and the cooling pipe can be seen in figure 5.

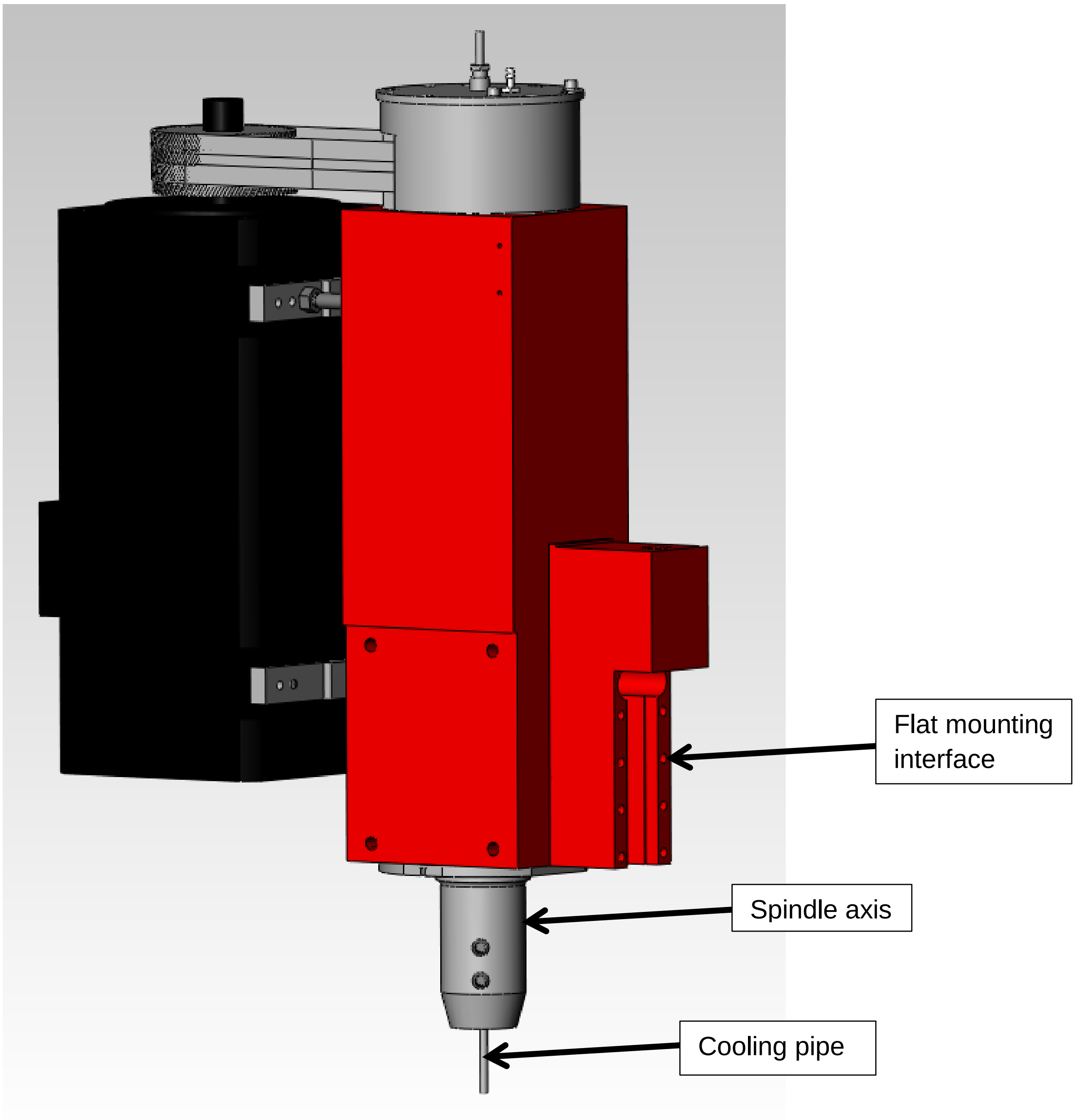


Figure 5: The lab machine interfaces

The prototype was going to be equipped with wire feeding. It was decided from ESAB to use one of their standard issue wire feeder and leveller. According to ESAB the welding wire had to be fed to directly to the Probe with an angle as large as possible to the horizontal plane, but not larger than 30 degrees. The welding wire was set to be a 2.4mm aluminium wire.

The lab machine is equipped with a hydraulic pump to create the down force of the Probe via a hydraulic cylinder. The same hydraulic pump had to be used to create the down force of the Shoulder. The hydraulic pump can deliver a maximum pressure of 180 Bar which was set as a maximum pressure for creating the down force of the Shoulder. By ESABs demands, the Shoulder should be able to apply a 10kN down force on the weld piece. The maximum pressure and the down force set restrictions on the minimum diameter of the hydraulic cylinder that could be used.

The 10kN down force from the Shoulder creates a horizontal friction force of 7kN when using the friction coefficient of 0.7 for steel against aluminium (see equation 2). The friction coefficient between steel and aluminium is around 0.61 (Reymon A., 2014) but a friction coefficient of 0.7 was used to ensure a safety margin. The friction value was important for analysis of the construction during the development.

$$F_{friction} = down\ force * \mu = 10{,}000 * 0.7 = 7kN \tag{2}$$

The maximum horizontal deflection of the Shoulder was set to 0.2mm from ESAB. This maximum deflection was set to avoid any moving parts to cut into each other and therefore ensuring a stable and safe welding procedure. The maximum deflection of the Shoulder set high demands on rigidity on the whole structure due to the high forces.

The prototype was designed to weld 5mm thick aluminium alloy plates, 5xxx and 6xxx, with a 90 degree angle using a Probe with a diameter of 8mm. The plates were going to be welded as a tee weld (see figure 6). The weld had to be done with full penetration, using a 0.5mm overlap and creating a 5mm fillet. The overlap is defined as the distance that the Probe penetrates the centreline of the vertical plate. An overlap of 0.5mm creates a 1mm overlap zone when welding a tee weld from both sides (see figure 6).

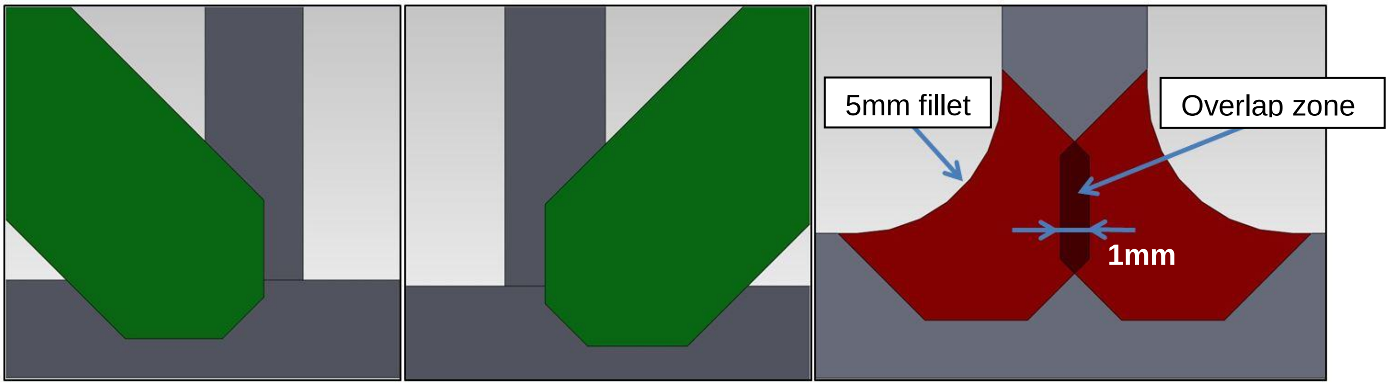


Figure 6: To the left and in the middle, schematic pictures of the Probe and weld piece during a weld are shown. To the right the weld zones (red) and the overlap zone (dark red) of 1mm can be seen

To be able to weld other material thicknesses, using larger Probes, the Shoulder had to be able to have a minimum stroke of 20mm independent of the lab machine. The stroke is also needed to perform the welding procedure, including separating the contact between Probe and Shoulder to avoid adhesion. To be able to weld other material thicknesses the Probe and Shoulder also needed to be made with interfaces allowing easy replacement.

A sliding contact between the Probe and the Shoulder was a precondition from ESAB. This sliding contact is needed so that the heated material cannot escape the weld upwards between the Probe and the Shoulder while welding. A sliding contact also allows the Shoulder to have a different down force than the Probe. Having independent down force between Shoulder and Probe was a precondition from ESAB.

The maximum welding speed that the prototype should be able to perform was set to 1.5m/minute while using a rotational speed of 3000rpm on the Probe. To ease the development of part 2 of the project as many parts as possible from part 1 should be able to be used for part 2. This meant leaving as much room as possible for incorporating preheating and cooling, and developing the parts that needed to be changed as easily changeable.

5 Concept generation Part 1

To satisfy the preconditions and fulfil the objective a function structure was set up. The functions were cladded together to form system modules that needed to be developed. These system modules are shown in figure 7. Several concepts were generated to all modules through different modes of brainstorming. These were systematically narrowed down through feasibility until a few remained. In this chapter the modules and the most promising concepts for each module will be described.

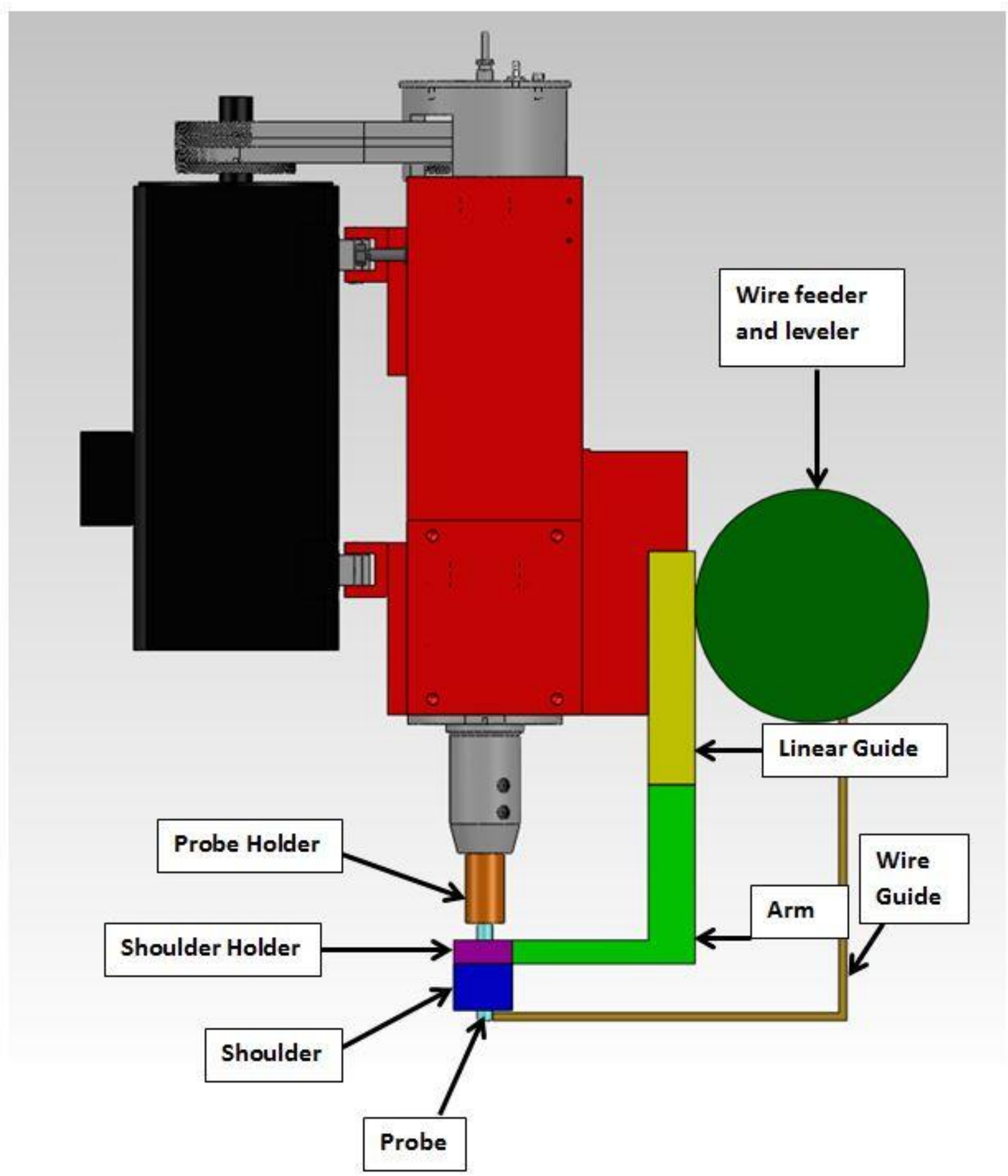


Figure 7: Schematic picture of all modules

5.1 Probe module

The Probe has the function of heating the weld piece to forging temperature and forcing the heated material downwards into the weld. The heat is created by friction between the Probe and the weld piece due to the rotation and the Probe.

5.2 Probe Holder module

To be able to connect the Probe to the rotating spindle axis on the current FSW lab machine, a Probe Holder was needed. It had to have interfaces to the spindle axis and to the Probe. This was to enable replacement of the Probe, according to specifications. By having a Probe Holder instead of attaching the Probe directly to the spindle axis, the Probe was allowed to have a simplified design.

5.3 Shoulder module

The main function of the Shoulder is to seal the heated material during the welding operation and to form the weld fillet. The Shoulder had to have a sliding contact to the Probe close to the weld. This is to prevent heated material from escaping the weld zone.

5.4 Shoulder Holder module

Since it was a requirement to have a replaceable Shoulder it was necessary to have a Shoulder Holder. This had the function of holding the Shoulder and connecting it to the rest of the construction.

5.5 Linear Guide module

Because of the forces present during the welding process, it was decided that a guiding system was needed. The guiding system has the function of guiding the construction as it is moved through its welding positions. It should also absorb some of the horizontal forces from the friction between the Shoulder and the weld piece, to reduce deflection. Included in the Linear Guide module is also the force generation function, which is the function that generates the pressure from the Shoulder to the weld piece. The force generation is predetermined to be based on hydraulics according to the preconditions.

5.6 Arm module

To be able to hold the Shoulder, Shoulder Holder and other possible welding modules that had to follow the linear movement from the stroke, it was decided that an Arm was needed. The Arm would be a complementary part to the other modules, with fastening interfaces to the modules that needed to follow the linear stroke of the Shoulder.

5.7 Wire Feeder and Leveller module

A standard wire feeding and leveller system from ESAB was decided to be used. This was a requirement from ESAB.

5.8 Wire Guide module

To be able to guide the welding wire from the Wire Feeder to the Probe a Wire Guide was needed. The Wire Guide would enable the welding wire to be controlled, ensuring safety and reliability of the welding operation. The welding wire would be guided directly to the Probe at an angle, according to preconditions from ESAB.

5.9 Probe concepts

The Probe's appearance depended heavily on the decided concepts for Shoulder, Shoulder Holder and Probe Holder since it has co-dependency to those modules. The design of the tip of the Probe was regarded as detailed development. This would be influenced by the design of the Probe from Company X. Most of the design would however be new since the requirements on the Probe from ESAB were different. The Probe would also be developed for welding aluminium with 5mm thickness, which was not tested by Company X. From ESAB, it was decided that the bottom part of the Probe, penetrating the material, would have a diameter of 8mm.

Since the requirements set a small span in the way the Probe could be developed not many concepts could be generated before detailed development. The concept choice that had to be made was regarding the general size of the Probe. The different Probe concepts can be seen in figure 8.

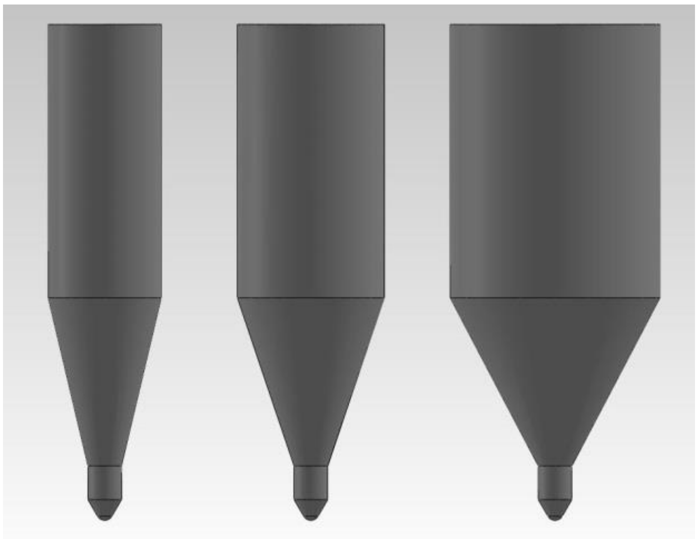


Figure 8: The picture shows the three different concepts for the Probe. From the left to the right: Probe small, Probe medium and Probe large

5.9.1 Probe large

The bottom diameter of the Probe was, as mentioned before, fixed. In the large Probe concept the upper part of the Probe had a relatively large diameter. This had the advantage of adding rigidity to the Probe and possibly lowering the horizontal displacements. This would however take up a large space in the Shoulder Holder since the upper part of the Probe had to go through the Shoulder Holder.

5.9.2 Probe medium

The medium Probe had medium sized upper part, hopefully adding some rigidity and still not taking up to much space in the Shoulder Holder.

5.9.3 Probe small

The small Probe had the smallest possible diameter while still being able to connect to the Probe Holder and holding the cooling pipe. It could possibly pose a risk of low rigidity and high displacements.

5.10 Probe Holder concepts

The interface to the spindle axis was set to be a 50mm Weldon interface. Since Weldon is the standard fastening system used at ESAB a Weldon interface was also chosen for the interface between the Probe Holder and the Probe as seen in figure 9. No other concepts were generated for this module. Other design aspects were regarded as detailed development.

Figure 9: 3D-view of the Probe Holder concept

5.11 Shoulder concepts

On a basic level the Shoulder would look much alike the Shoulder from the Company X solution. This is because their solution worked well in tests. No other benchmarking opportunities existed since the stationary Shoulder principle is patented and only explored by Company X. The Shoulder needed however to be modified for wire feeding, keeping a seal at the front of the Shoulder and welding 5mm aluminium. These modifications were regarded as detailed development. A rough 3D-model can be seen in figure 10.

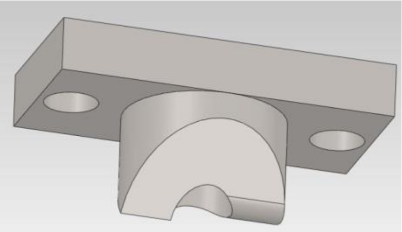


Figure 10: 3D-view of the Shoulder concept

5.12 Shoulder Holder concepts

The Shoulder Holder has the main function of holding the Shoulder and connecting it to the Arm. The Shoulder Holder interface to the Shoulder was determined by the Shoulder design. The Shoulder Holder also has the function of adding rigidity to the Shoulder and Probe. Adding rigidity to the Probe was the function regarded during the concept generation.

5.12.1 Ball bearing to Probe

This concept included a ball bearing between the Shoulder Holder and the Probe (see figure 11). A ball bearing has almost no friction, which results in low heat and possible long lifetime. The ball bearing is a large bearing, this result in little space in the Shoulder Holder of future cooling and heating concepts.

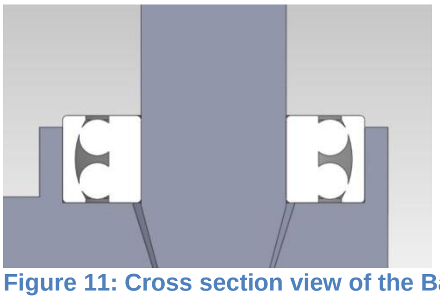


Figure 11: Cross section view of the Ball bearing to Probe concept

5.12.2 Slide bearing to Probe

This concept had a slide bearing between the Shoulder Holder and the Probe as seen in figure 12. A slide bearing takes up less space than a ball bearing, leaving more space available in the Shoulder Holder.

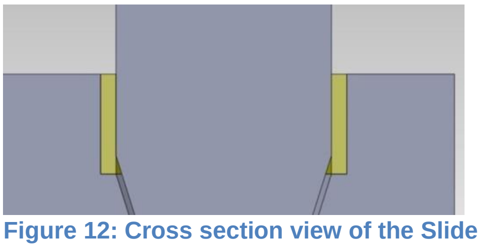


Figure 12: Cross section view of the Slide bearing to Probe concept

5.12.3 No bearing to Probe

This concept had no bearing between the Shoulder Holder and the Probe (see figure 13), thus only relying on the sliding contact between the Probe and the Shoulder. This would give the largest amount of space available at the Shoulder Holder but could cause high displacements and possibly a risk of pinching.

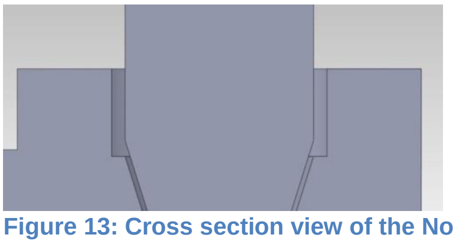


Figure 13: Cross section view of the No bearing to Probe concept

5.13 Linear Guide concepts

After the initial benchmarking and screening was conducted it was decided that the Linear Guide concept should be a rail guide, consisting of a rail and two wagons. The differencing factors were the placement of the rail system and the placement of the hydraulic cylinder. The length of the rail would be decided in detailed development.

The placement of the hydraulic system relative to the rail system could either enhance or reduce the torque (A) on the rail system as seen in figure 14. On the left picture the hydraulic cylinder is placed closer to the lab machine than the rail, acting on the arm with the force F3 (see figure 14), and by that reducing the torque (A) on the rail system. The right picture shows the hydraulic cylinder placed further away from the lab machine than the rail, acting on the arm with the force F2 (see figure 14), and by that enhancing the torque (A) in the rail system.

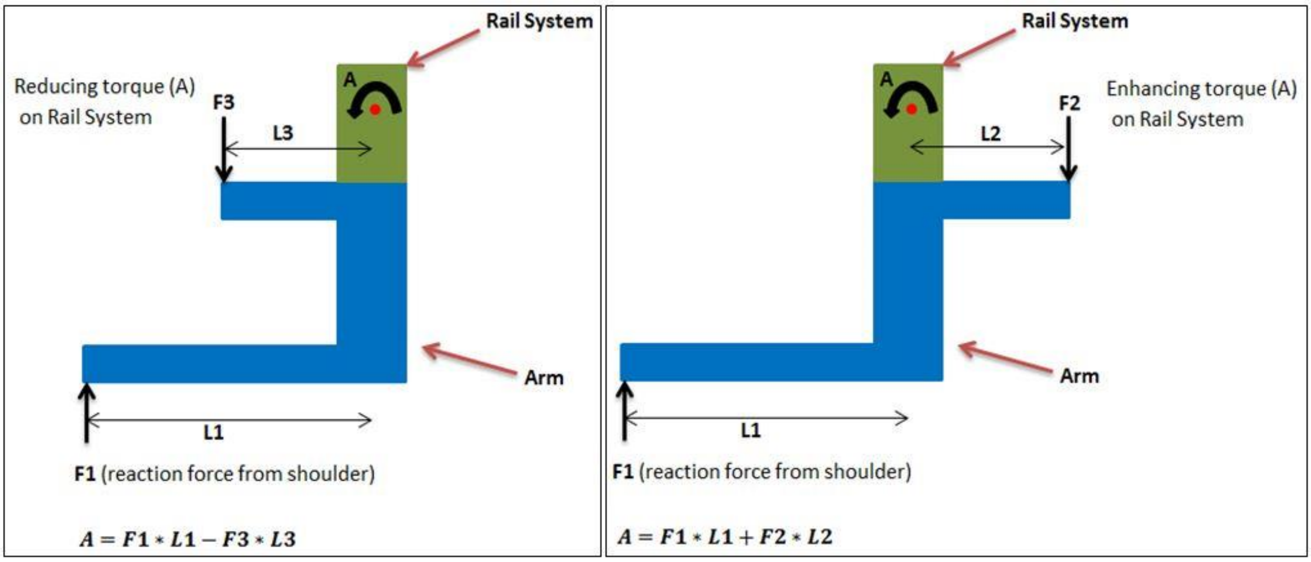


Figure 14: Rail system torque effect of hydraulic cylinder placement

5.13.1 Enclosed Wagon

The guiding is performed with a wagon and rail system that is placed inside the mounting interface at the side of the lab machine as seen in figure 15. This gives a compact design with a small lever to the Shoulder, and thus small forces on the rail system. It poses size limitations on the upper part of the Arm and the guide system since it needs to fit inside the hollow space inside the mounting interface. The hydraulic cylinder was placed in front of the rail system and by that enhancing torque effect on the rail system.

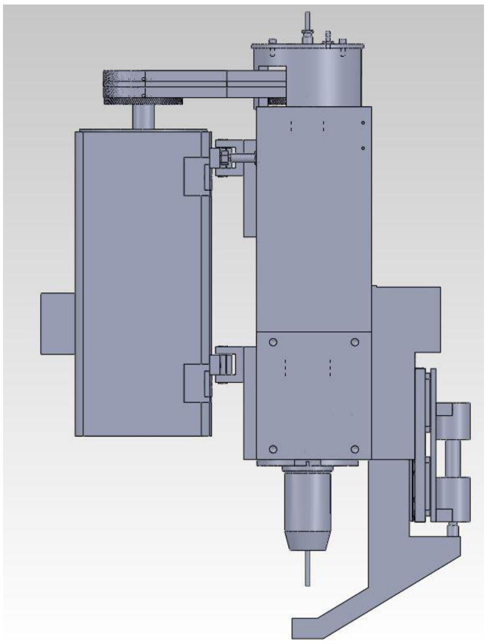


Figure 15: 3D-view of the Enclosed Wagon concept

5.13.2 Outside Wagon

This concept was similar to the Enclosed Wagon concept. In this concept the guide system was placed outside the mounting interface (see figure 16), this gave a more bulky design but posed no restrictions on the size of the Arm or the rail system. Similar to the Enclosed Wagon concept the hydraulic cylinder was placed in front of the rail system, thus enhancing the torque on the rail system. This concept was benchmarked from another Linear Guide system at an ESAB weld machine, used for other applications.

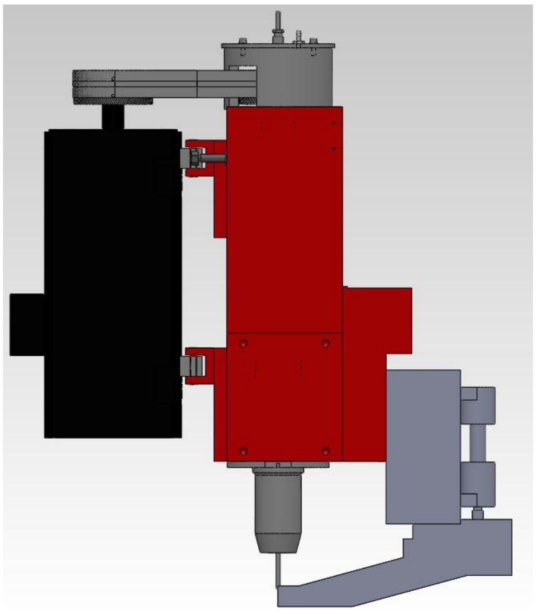


Figure 16: 3D-view of the Outside Wagon concept

5.13.3 Outside New

In the Outside New concept the hydraulic cylinder was placed behind the rail system as seen in figure 17. This reduced the torque on the rail system. Similar to the Outside Wagon concept it gave a bulky design. The optimal design of this concept would be to have the hydraulic cylinder placed inside the mounting interface of the lab machine. This was however not possible due to the size of the hydraulic cylinder.

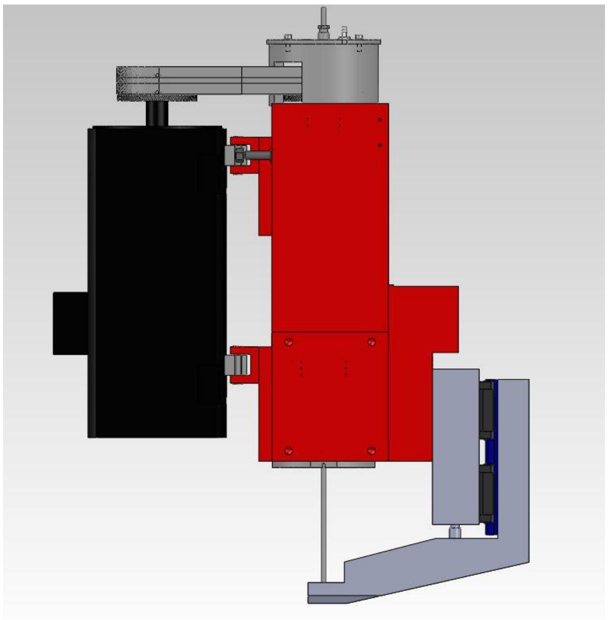


Figure 17: 3D-view of the Outside New concept

5.14 Arm concepts

The Arm was a complementary module, meaning that the design depended on the connecting modules. The function of the Arm that needed to be evaluated before detailed development was the connection to the Shoulder Holder.

5.14.1 Integrated Shoulder Holder

In this concept the Shoulder Holder module is integrated in the Arm as seen in figure 18. This gave a compact design but makes the Arm complex and eliminates the possibility to change the Shoulder Holder.

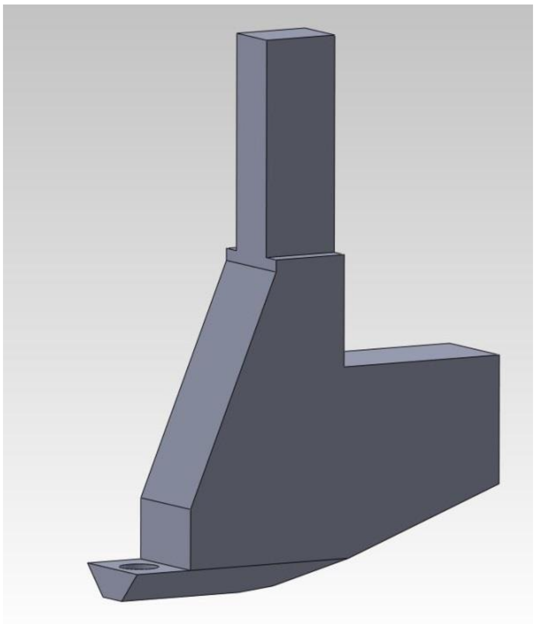


Figure 18: 3D-view of the Integrated Shoulder Holder concept

5.14.2 External Shoulder Holder

This concept consists of an Arm that only works a complement to the other modules. The Shoulder Holder is in this concept separate and fastened to the Arm as seen in figure 19.

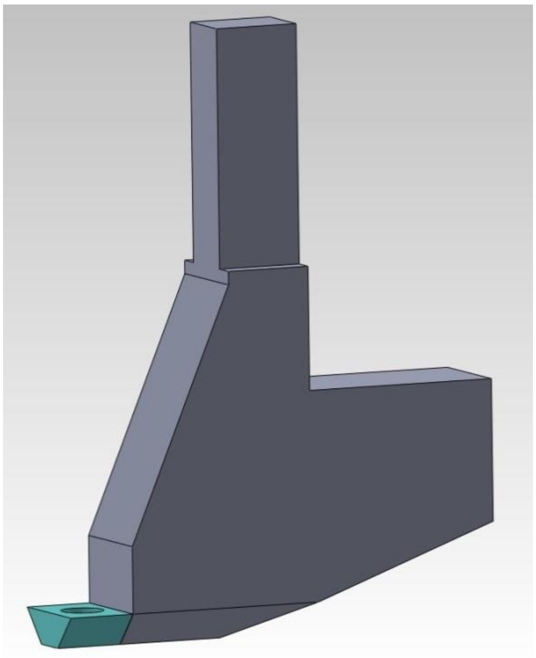


Figure 19: 3D-view of the External Shoulder Holder concept

5.15 Wire Feeder and Leveller concepts

Since a standard ESAB Wire Feeder and Leveller system was predetermined, only the decision of placement remained. To be able to avoid tensional stress in the welding wire it was decided that the Wire Feeder and Leveller needed to move with the stroke of the Shoulder. This had the implication that the Wire Feeder and Leveller needed to be mounted on the Arm. The interface was decided to be developed in detailed development. A Wire Feeder and Leveller from ESAB can be seen in figure 20.

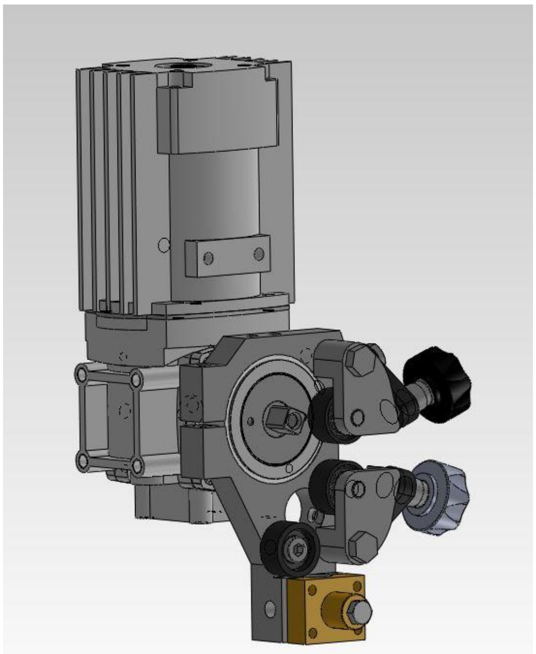


Figure 20: 3D-view of the Wire Feeder and Leveller

5.16 Wire Guide concepts

The Wire Guide had the function of guiding the welding wire to the Probe. After an initial screening, two concepts remained. The concepts included guiding the welding wire from the Leveller to the end of the Arm. Guiding the welding wire from the Arm to the Probe was regarded as detailed development since it depended on the Shoulder, Shoulder Holder and Probe design.

5.16.1 Grooved path

In this concept a grooved path in the Arm guides the welding wire (see figure 21). Cover plates are placed over the groove to hold the welding wire in place.

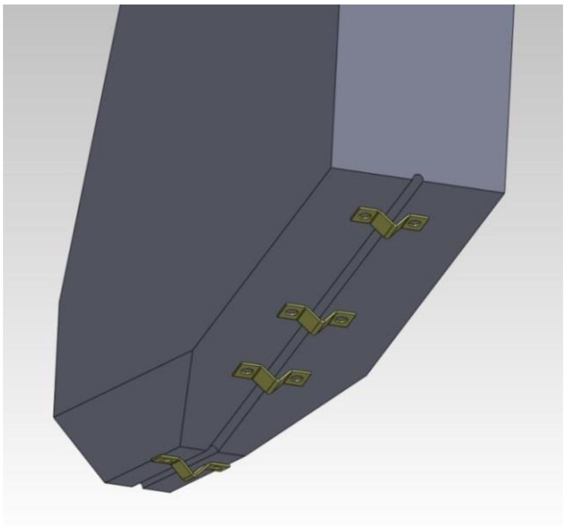


Figure 21: 3D-view of the Grooved path concept

5.16.2 Long pipe

A pipe guide mounted on the Arm guides the welding wire to the end of the Arm as seen in figure 22.

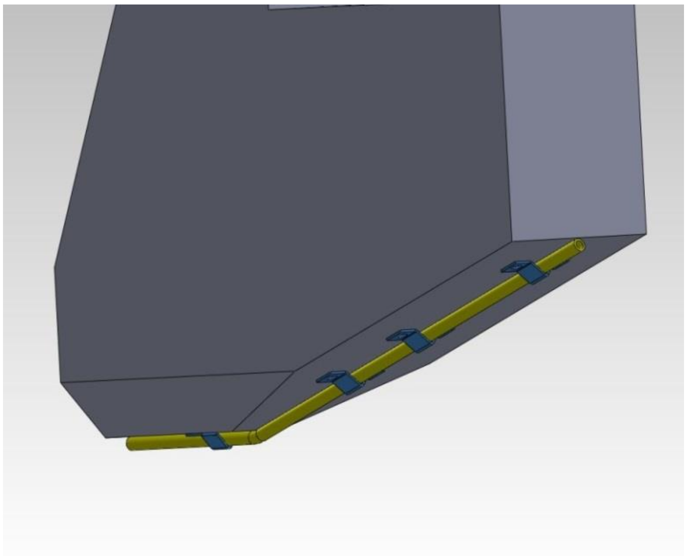


Figure 22: 3D-view of the Long pipe concept

6 Concept selection Part 1

The developed concept would work as a prototype. The prototype would be used as a testing device, testing the feasibility and discovering opportunities and limitations on the stationary Shoulder FSW process. It would also work as a demonstration device for customers. Because of these preconditions the focus in the selection process was to find the concepts that were most promising when it comes to adjusting to the preconditions and resulting in a stable construction.

6.1 Probe

The different Probe concepts were evaluated in ANSYS (see appendix A3). The decision criteria were the Shoulder horizontal deflection, the stress of the Probe together with the size of the Probe. The analysis showed that the stresses on the Probe were low compared to the yield strength for construction steel. Furthermore, the different sizes did not result in any notable difference in horizontal deflection. Due to these facts, the small Probe was chosen. This would provide the most available space in the Shoulder Holder.

6.2 Shoulder Holder

The Shoulder Holder had the main function of adding replacement functionality to the Shoulder as well as adding rigidity to the Probe and the prototype in general. The different bearing options were investigated through researching of available and feasible options. The bearings was also analysed in ANSYS, were the resulting stresses on the bearings and the Probe were investigated (see appendix A3). The modes guiding the decision were the size of the bearing, the resulting Probe forces and the horizontal deflection of the Shoulder.

Through the analysis it was discovered that a bearing to the Probe would greatly add to the rigidity of the construction, lowering the horizontal deflection and the stress of the Probe. Because of this the No Bearing concept was disregarded. The stress on the bearing was low and could easily be managed by both the Ball Bearing and the Slide Bearing concepts. Since a ball bearing has a bulkier design, the Slide Bearing to Probe concept was chosen. Aside from the bearing stress, the rotational speed also needed to be evaluated to choose an appropriate slide bearing. This was regarded as detailed development.

6.3 Linear Guide

The decisive demands on the Linear Guide were to find a concept that resulted in small forces on the rail system and small resulting deflections in the horizontal direction on the Shoulder. The forces on the rail system were tested to ensure safety and longevity of the rail system and the horizontal deflection was tested to meet the preconditions from ESAB. This was tested using FEM simulations in ANSYS. The analysis was tested in different steps, with different accuracy. Although many of the simulations were simple and probably not realistic, they worked well as a comparison tool for discovering strengths and weaknesses in the evaluated concepts.

The Outside Wagon concept was presumed to have the largest deflections and largest forces on the rail system. This is due to the fact that that the construction provides a larger torque than the Compact Wagon concept since the wagons are further away from the welding position. Another aspect was that the concept did not have the advantage of having the cylinder placed closer to the lab machine than the wagons, as in the Outside New concept. Having the cylinder placed closer to the lab machine leads to a reduced torque on the rail system. This presumption was tested and confirmed in a simple ANSYS simulation (see appendix A1). Hence the Outside Wagon concept was disregarded.

The two remaining concepts were then tested in a more detailed ANSYS simulation (see appendix A2). This was done to be able to identify the better concept and to get a picture of how large the deflections and forces on the rail system were. This would thus provide valuable input for the detailed design of the module. The Compact Wagon had the advantage of a more compact construction while the Outside New concept had the advantage of having the hydraulic cylinder placed closer to the welding position. From the simulation it can be seen that the forces on the rail system were similar for the two concepts. The Compact Wagon had a significantly lower horizontal deflection than the Outside New concept. Due to this, the chosen concept was Compact Wagon.

6.4 Arm

The Arm concepts were evaluated through feasibility and manufacturability in collaboration with responsible actors at ESAB. Since the product is going to be used for testing it was desired to have the ability to easily change parts. Therefore it was decided to use the External Shoulder Holder concept. This concept was also favourable from a manufacturing point of view since it would result in a less complex design.

6.5 Wire Guide

In the same way as with the Arm the Wire Guide concept was decided through feasibility and manufacturability. The Long Pipe concept provides a more simple design with the availability to change pipe if other welding wire dimensions are needed. Hence that concept was chosen.

7 Final concept part 1

For the final concept the different modules were developed in parallel since decisions and changes often affected several modules. The development was done in consultation with ESAB and the suppliers of the sourced parts. All drawings can be found in appendix D1, the drawing measurements have been blurred due to confidentiality. The measures stated in this chapter have also been slightly altered. The drawings are in Swedish from ESAB's request. Unless otherwise stated, the material for the parts is construction steel S355J2 or S235JR.

7.1 Probe

The focus was to create a robust Probe while still having a simple design. Many of the features of the Probe could be taken from the Company X solution, but these had to be modified to work with the developed concept. The material of the Probe was set to be QRO 90, hardened to HRC 47-49. This is the material used in Probes for butt welding at ESAB. The Probe stress from horizontal deflection has been investigated in ANSYS to 33.8MPa (see appendix A4). The stress was far below the yield strength of the QRO 90 material, which is 1620MPa (Uddeholm, 2011). Having a high strength material was still a necessity due to the high wear of the Probe during welding. The final design of the Probe can be seen in figure 23.

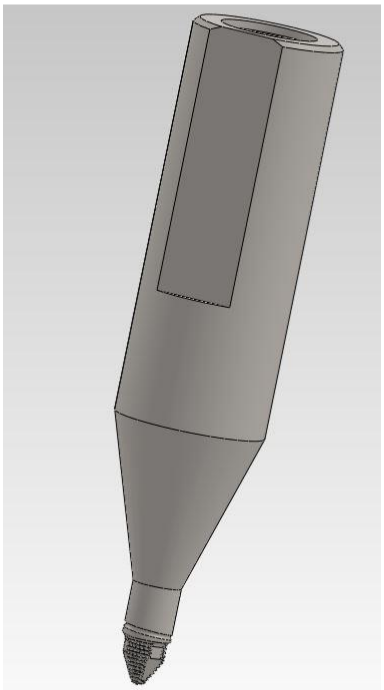


Figure 23: The picture shows a 3D-view of the Probe

Through the development of the Probe a large effort was on the construction of the Probe tip. The Probe tip had to have a 0.5 mm overlap of the weld pieces when welding a tee weld according to the preconditions. The angle of the Probe was set to 60 degrees (see figure 24) in accordance to the Company X solution. This gives a good surface piercing end ensures a 0.5mm overlap without over penetrating the weld pieces. The Probe also had to have a threaded surface to force the heated material and the welding wire downwards to the weld. Furthermore, the Probe had a sliding contact to the Shoulder just above the threaded surface.

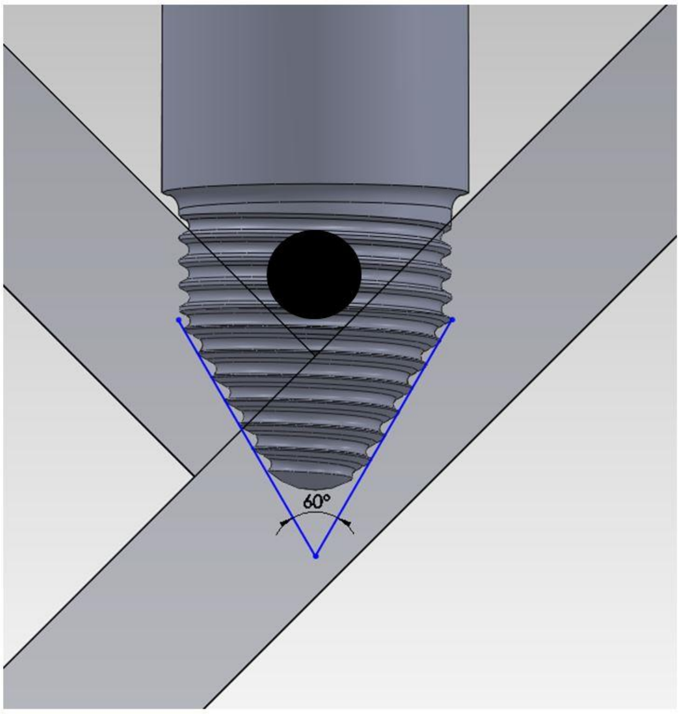


Figure 24: The picture shows the 60 degree angle of the Probe tip. The black circle represents the weld wire. The flat surface above the threaded area is where the sliding contact to the Shoulder will occur. The weld pieces of tee weld can be seen in transparent

The upper part of the Probe has a coned interface to be able to reach a larger diameter and thus adding rigidity and enabling interface to the Probe Holder. This cone needed to have a distance to the Shoulder and Shoulder Holder to avoid transferring vertical force from the Probe to the Shoulder package. Avoiding transference of vertical force was essential to ensure that the Probe pressure was independent of the Shoulder pressure, in accordance with the preconditions. To ensure further robustness it was decided that the Shoulder Holder would hold a bearing to the Probe. Details of this bearing can be found under the Shoulder Holder sub chapter in section 7.4. The design was set up with a 2mm distance between the cone of the Probe and the cone of the Shoulder and Shoulder Holder as shown in figure 25. A distance of 1mm was set between the bearing and the Probe Holder, making it the contact point if the Probe would be lowered down too far.

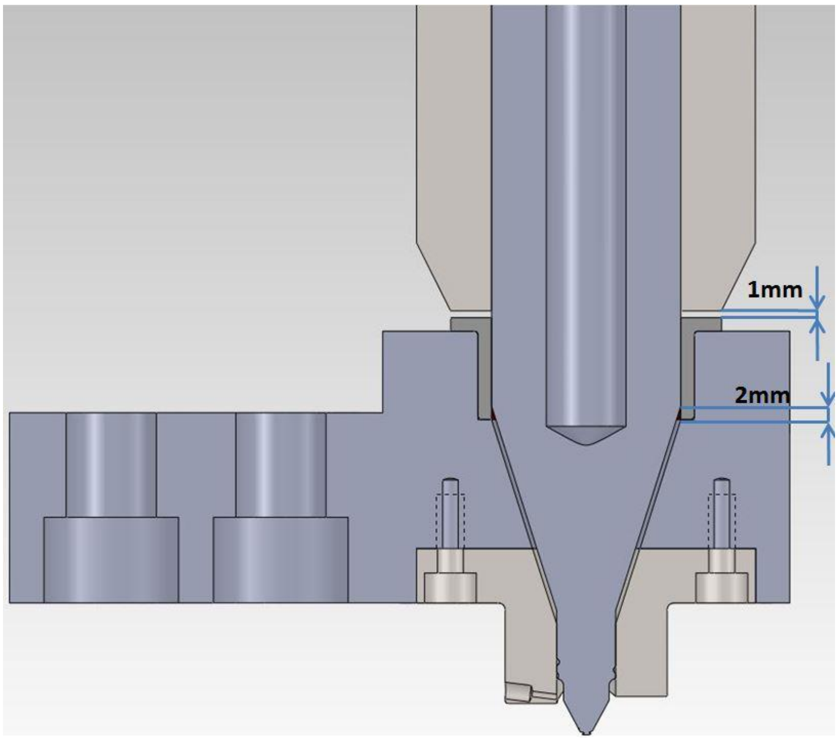


Figure 25: The picture shows the safety distance between the cone of the Probe and the cone of the Shoulder and Shoulder Holder (2mm). It also shows the safety distance between the Probe Holder and the bearing (1mm).

The design of the bearing also had a role in deciding the upper diameter of the Probe. A bearing diameter that enabled enough rigidity while still not creating too much heat was desired. These dependencies caused design issues not only to the Probe, but also to the Shoulder and the Shoulder Holder. The measures of the threaded surface, the slide area and the cone of the Probe needed to be in accordance with the cone height and angle of the Shoulder and Shoulder Holder. All this while still keeping the penetration overlap close to 0.5mm.

To be able decide the measurements of the Probe a Matlab script was developed (see appendix C1). The Matlab script included all measures of the Probe, the Shoulder and the Shoulder Holder. The contact height from the Probe to the Shoulder and the contact height and diameter of the bearing was decided to be the controlling measurements. This is since these measures have a big influence over the rigidity of the construction.

The Probe was designed to have an interface for the cooling pipe from the lab machine. This interface is a drilled hole at the top of the Probe. The hole has a depth to ensure cooling of the bearing. An O-ring interface was constructed at the top of the Probe to ensure a dry environment. The interface to the Probe Holder was decided to be a Weldon interface, since it is a proven concept at ESAB. All the interfaces can be seen in figure 26.

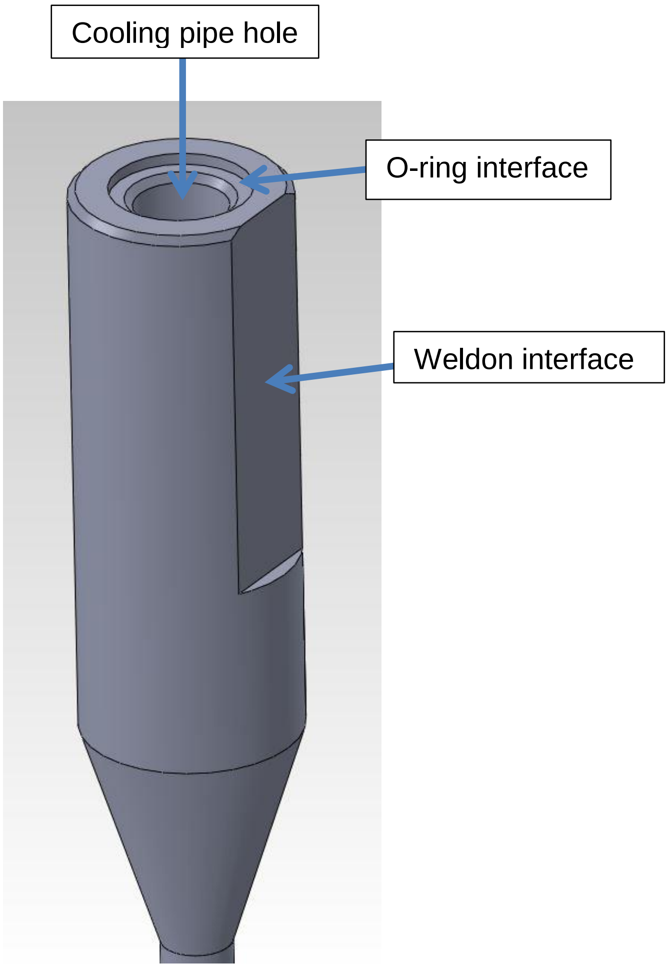


Figure 26: The picture shows the Weldon and O-ring interfaces on the Probe as well as the drilled hole for the cooling pipe.

The design of the threads (see figure 27) on the Probe was decided in accordance with the Company X solution since it is the only workable solution found, and no knowledge about what is really happening in the welding process was available. The threaded interface was however modified for a different Probe diameter and a different threaded height to enable wire feeding. The threads where milled down on three positions equispaced radially to create chaos in the weld. The chaos ensures that imperfections and hard surface layers are evenly distributed and does not end up at the bottom of the weld zone. A coarse thread was also added on the sliding surface, this is to push down any material that might move upwards from the pressure in the weld.

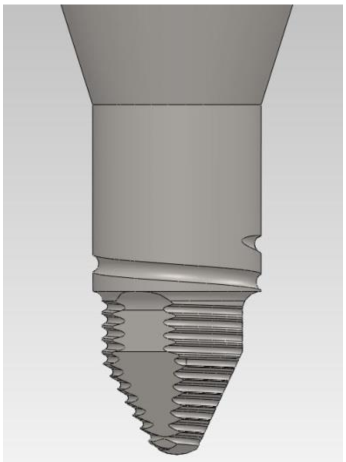


Figure 27: The picture shows the threads on the Probe. The thread highest on the Probe is the coarse thread. The picture also shows one of the milled down surfaces.

7.2 Probe Holder

As mentioned in the Probe chapter, it was decided to have a Weldon interface between the Probe and the Probe Holder. This is the same interface as the one between the Probe Holder and the spindle axis of the lab machine. The design of the Probe Holder was also heavily controlled by the design of the Probe. The lower part has the Weldon interface to the Probe with a diameter settled by the Probe design as seen in figure 29. The height of the Probe Holder was decided by the fact that the cooling pipe needed to reach the bearing. This was to ensure high durability of the bearing. Since the cooling pipe runs through the Probe Holder an O-ring interface was made on the Probe Holder to prevent water leakage (see figure 28).

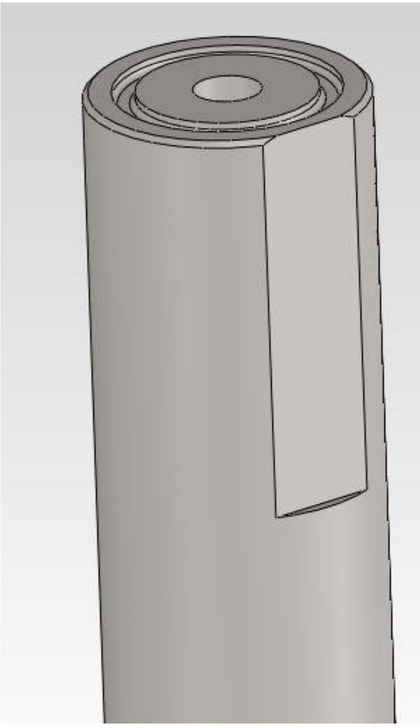


Figure 28: The picture shows the Weldon interface for the spindle axis and also the O-ring interface

Figure 29: The picture shows the Weldon interface for the Probe

7.3 Shoulder

The dimensions for the rectangular part of the Shoulder were influenced by Company X's Shoulder design, knowing this would give a ridged enough interface between the Shoulder and the Shoulder Holder. The Shoulder is attached to the Shoulder Holder with two M4 screws. The material of the Shoulder was set to be the QRO 90, as in the Probe. This is to avoid abrasion, since the Probe and the Shoulder has a sliding contact. The front of the Shoulder has a sharp edge to be able to prevent heated material to escape in the welding direction. The back of the Shoulder was designed with a radius of 5mm to be able to create a 5mm fillet on the weld piece. Both the radii and the sharp edge of the Shoulder can be seen in figure 30.

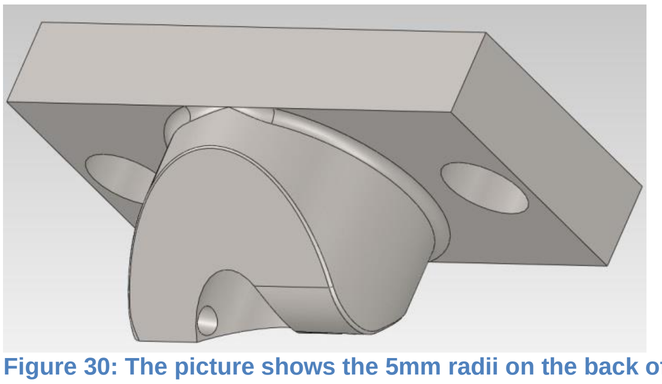


Figure 30: The picture shows the 5mm radii on the back of the Shoulder and the 90 degree angle in the front of the Shoulder

The dimensions for the conical hole that goes through the Shoulder (see figure 31) were calculated with the Matlab script which can be found in appendix C1. The Shoulder was designed with a 90 degree angle so that it can create a tight seal to the weld piece. Through the front of the Shoulder there is a hole serving as a Wire Guide through the Shoulder (see figure 31). The start of the hole has a larger diameter, serving as interface for the Wire Guide. The holes are concentric and have an angle of 7 degrees to the horizontal plane. The angle was decided to be as large as possible without making the structure weak. The purpose of the angle is to help to push the welding wire down to the weld zone.

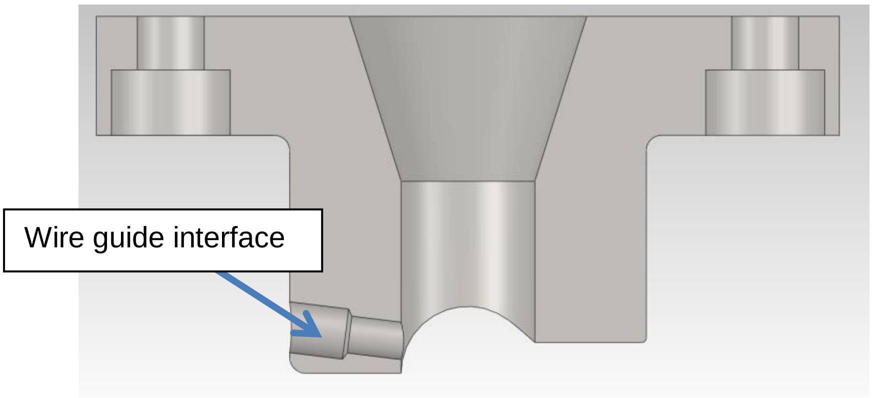


Figure 31: Cross section view of the conical hole and the Wire Guide interface

7.4 Shoulder Holder

The main function of the Shoulder Holder is to add replacement possibilities of the Shoulder. The interface for the Shoulder in the bottom part of the Shoulder Holder is made to fit and enclose the rectangular part of the Shoulder as seen in figure 32. The Shoulder can easily be replaced by removing two M4 screws.

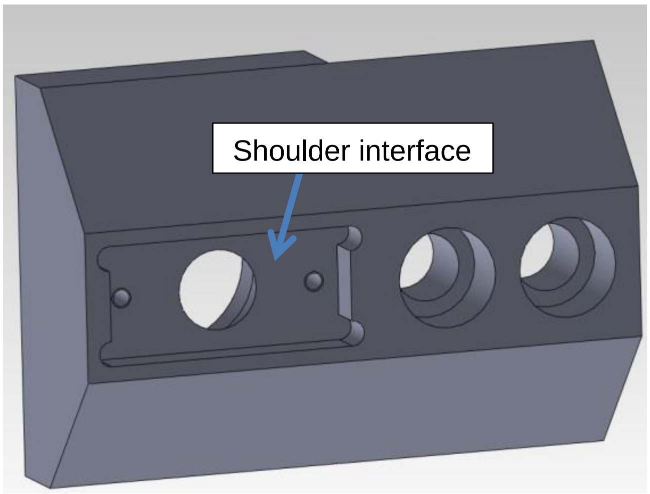


Figure 32: The picture shows the interface for the Shoulder

In the same way as the Shoulder, the Shoulder Holder has an angle of ninety degrees. The chamfered sides of the Shoulder and Shoulder Holder are parallel but not collinear. The chamfered sides on the Shoulder Holder have 1mm distance from the weld piece and in that way avoiding friction between them (see figure 33).

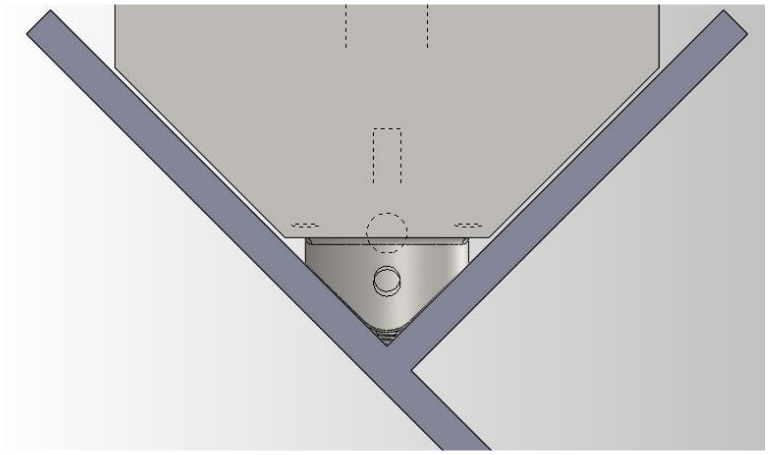


Figure 33: The picture the gap between the Shoulder Holder and weld piece

In figure 34 the interface to the Arm can be seen. The interface is made with an elevation that is slid in the contrary interface on the Arm, giving rigidity to the structure. The Shoulder is fastened with two M12 screws into the Arm.

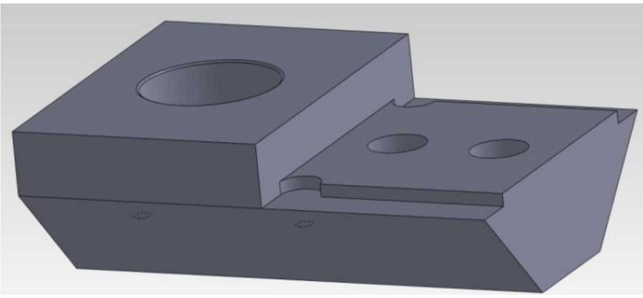


Figure 34: The picture shows the fastening interface for the Arm

The dimensions for the conical hole (see figure 35) in the Shoulder Holder were calculated with the Matlab script in appendix C1. The Shoulder Holder also contains an interface for a bearing. This bearing (see figure 36) helps to stabilise the Probe from the large frictional force during welding. The bearing is a PTFE flange bearing from the company Lagermetall.

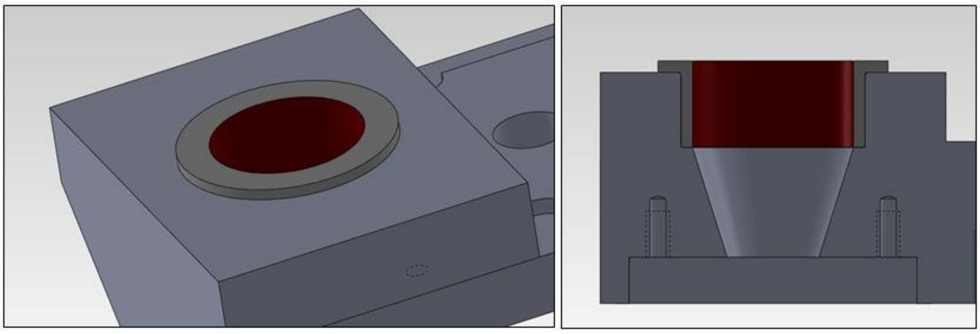


Figure 35: The picture to the left shows the bearing fitted in the Shoulder Holder. The picture to the right shows a cross-section view of the bearing and the Shoulder Holder

The flange (see figure 35) works as safety if the Probe would be lowered down too far. Instead of the Probe Holder getting steel to steel contact with the Shoulder Holder, it will slide on the flange of the bearing. This flange also prevents the cone of the Probe to clash with the Shoulder if lowered down too far.

According to the performance data on Lagermetalls homepage for the chosen bearing it can easily handle the forces during the welding procedure. The maximum sliding speed is only allowed to be 3.5m/s (Lagermetall, 2014). The sliding speed on the bearing will be 4.4 m/s, when calculating with the maximum rotational speed 3000 rpm of the Probe (see equation 3).

$$
\begin{gathered}
\text{D}= Inner\ diameter\ bearing = 0.028m \\
\omega = 3000\, rpm \\
O = D * \pi = 0.088m \\
v_{bearing} = \frac{O * \omega}{60} = \frac{0.088 * 3000}{60} = 4.4\, m/s
\end{gathered} \tag{3}
$$

Although the maximum value was exceeded, Lagermetall did not see it as a problem. This was due to the fact that cooling was set to be used, the forces were far from the given limits and each welding process was relatively short. ANSYS simulation also showed that the stresses on the bearing were far below limits as seen in appendix A4.

7.5 Linear Guide

The Linear Guide holds several functions. It anchors the wagons to a mounting plate, which in turn is anchored to the weld machine. This is the interface that holds the whole construction to the lab machine. On the other side of the mountain plate a hydraulic cylinder is mounted. The hydraulic cylinder has the ability to move the Arm vertically in relation to the lab machine. The hydraulic cylinder has a maximum stroke of 40mm, but the stroke is limited by the wagon and rail system to 35mm. This is still well above the specified minimum of 20mm to be able to clear the Probe from the Shoulder and thus avoiding adhesion.

The wagons have a sliding interface to a rail that is fastened to the Arm. This part of the Linear Guide is located inside the mounting interface of the lab machine, thus providing a compact construction. The Arm can then move vertically independent of the lab machine with the pressure provided by the hydraulic cylinder. The Linder Guide with its components as well as the arm and the lab machine can be seen in figure 36.

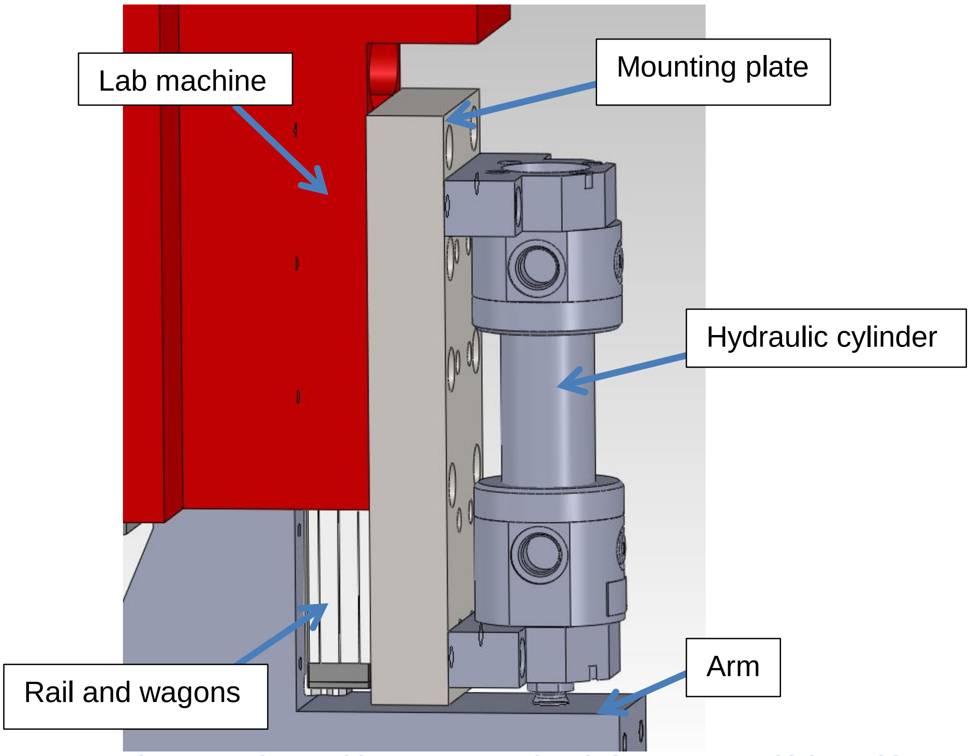


Figure 36: Liner Guide components in relation to Arm and lab machine

The hydraulic cylinder (see figure 37) is a Rexroth cylinder with a piston diameter of 32mm. At its nominal pressure of 160 bar it can provide a maximum force of 12.9kN (se equation 4), which is well above the required force of 10kN.

$$A = \frac{D^2 * \pi}{4} = \frac{0.032^2 * \pi}{4} = 8 * 10^{-4} m^2$$
$$P = 160\ bar = 160 * 10^5 Pa$$
$$F = P * A$$
$$F_{cylinder} = P * A = 160 * 10^5 * 8 * 10^{-4} = 12.9\ kN \qquad (4)$$

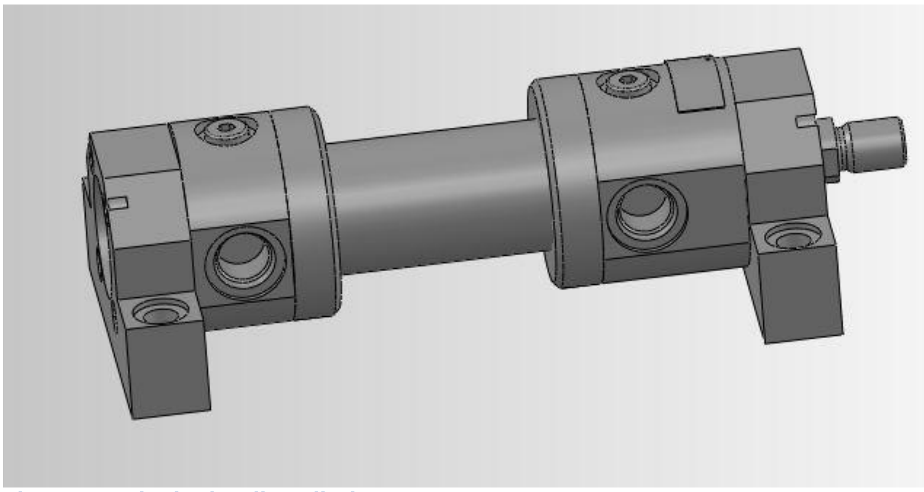


Figure 37: The hydraulic cylinder

The wagon and rail system (see figure 38) is from the company Aluflex. They are 25mm wagons that have an outer width of 45mm. This was important since they had to fit inside the 50mm width of the lab machine mounting interface. Two wagons are used to provide torque support from the forces created during welding. The forces on the wagons are tested and verified in ANSYS (see appendix A4). The rail has a length of 266mm. This was the minimum length available at Aluflex, it provided enough length to ensure the stroke required and to hold two wagons. Longer rails were tested to investigate the impact on the deflection. The tests were made in ANSYS and the results showed no evidence of an advantage with longer rails as seen in appendix A4.

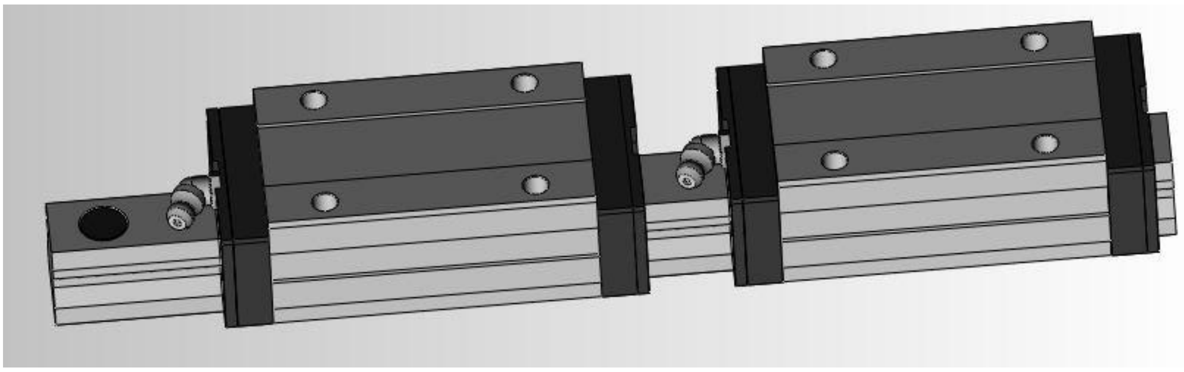


Figure 38: 3D-view of the rail and the wagons

The mounting plate (see figure 39) has M12 holes to screw it to the lab machine since this was the present mounting interface. These holes are recessed to avoid clashing with the hydraulic cylinder. To fasten the wagons, M6 recessed holes are also drilled in the mounting plate. The hydraulic cylinder is fastened by M10 screw, so the mounting plate also has M10 threaded holes to support that interface.

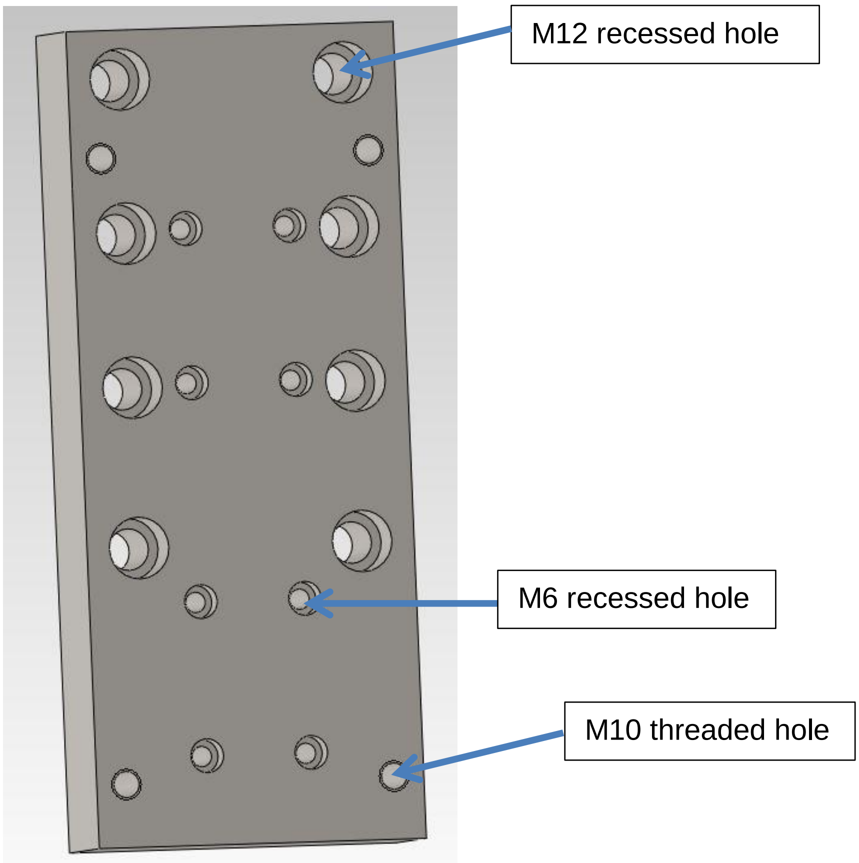


Figure 39: 3D-view of the mounting plate

7.6 Arm

The Arm (see figure 40) is a support module that enables fastening of other modules and transferring of force. Because of this, the Arm has several interfaces that are dependent on the design of the other modules.

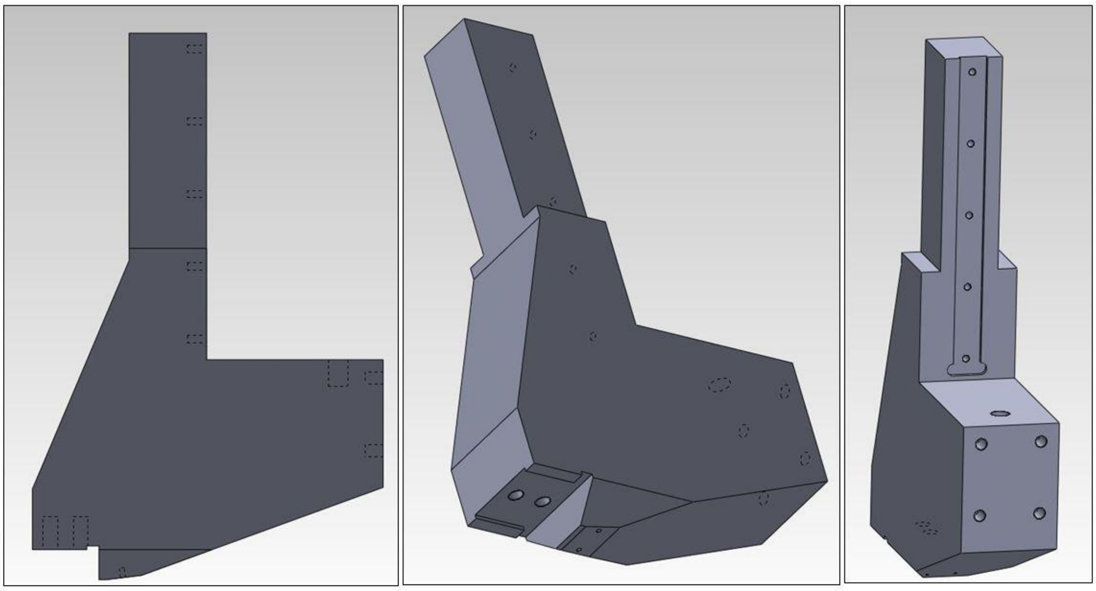


Figure 40: To the left is a picture of the arm from the side, in the middle is a picture of the arm from below and the picture on the right show the arm from the back

The bottom of the Arm has a milled rail interface to the Shoulder Holder as seen in figure 41. The Arm has two M12 threaded holes for fastening of the Shoulder Holder. The design of the interface gives a high rigidity in the torque direction. The bottom of the Arm also supports fastening of the Wire Guide by two M6 threaded holes on a flat 7 degree surface, in accordance with the wire insertion angle.

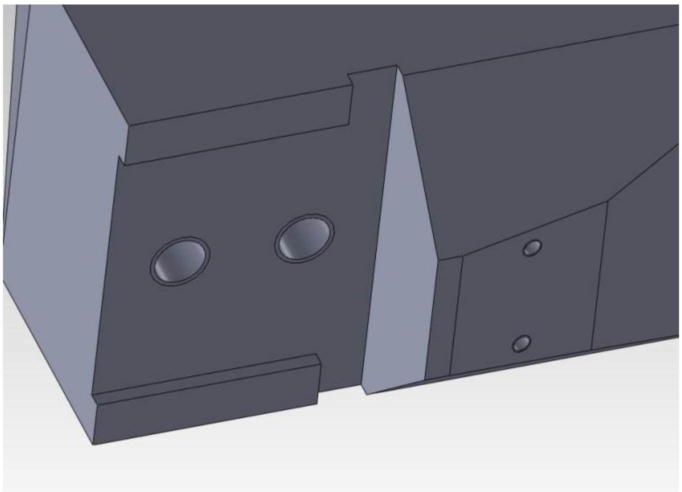


Figure 41: The picture shows a detailed view of the arm from below showing the interface for both Shoulder Holder and Wire Guide

The Arm has a milled recessed interface with five M6 threaded holes for fastening of the guide rail (see figure 42). The part of the Arm that is placed in the lab machine box is milled down to 47mm to fit inside the mounting interface of the lab machine. The rest of the Arm is 80mm wide to provide a robust construction. A flat surface with an M16x1.5 tapped hole is also provided for force transferring of the hydraulic rod. The back of the Arm has four M10 threaded holes for fastening of the wire feeding system. The rest of the Arm was designed to enable as high rigidity as possible.

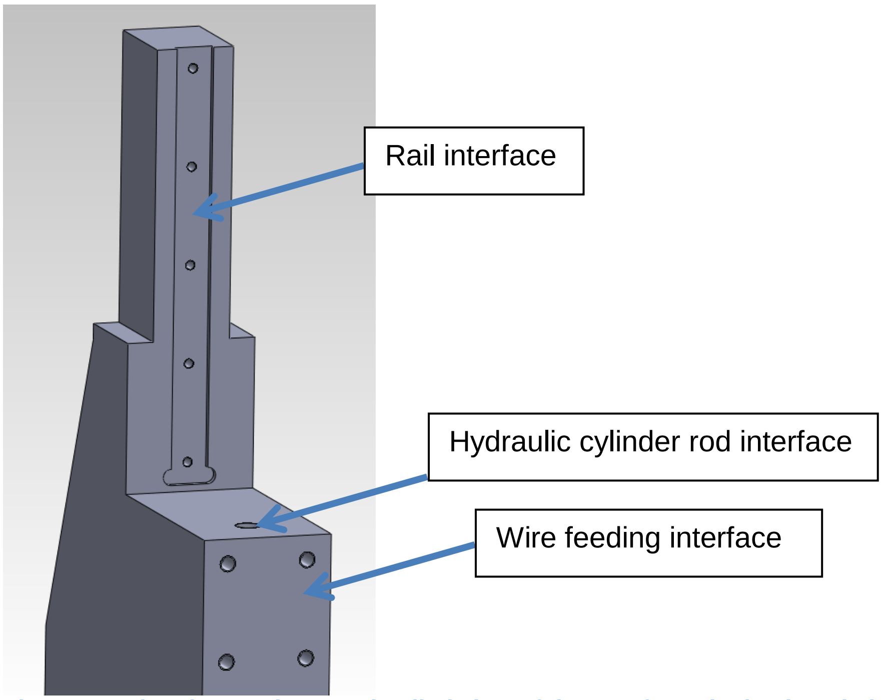


Figure 42: The picture shows a detailed view of the arm from the back and shows the interface for the rail, hydraulic rod and wire feeding system

7.7 Wire Guide

The Wire Guide connects to the Shoulder in the 7 degree hole. The other side of the Wire Guide is connected to the Arm by a bent plate (Pincher). Due to manufacturability the Wire Guide was divided into two parts that are screwed together. The material selection was based on the thermal conductivity of the material and the standard component availability. Having a material with high thermal conductivity was essential for preparing for the preheating of the welding wire in the part 2 development. The material was selected to be copper for the part closest to the Shoulder (Wire Guide Conical) and brass for the connecting part (Wire Guide Straight), fastened to the Arm. The sourced components are round bars that are lathed and drilled according to specifications.

In the concept generation a long pipe was set to be used as Wire Guide. After consultation with ESAB it was decided that a plastic tube would be used for the main part of the guiding. The tube was set to be screwed to the Wire Guide and to the interface with the Leveller. This is in line with the standard use of wire feeding at ESAB. The Wire Guide and the connecting plastic tube can be seen in figure 43.

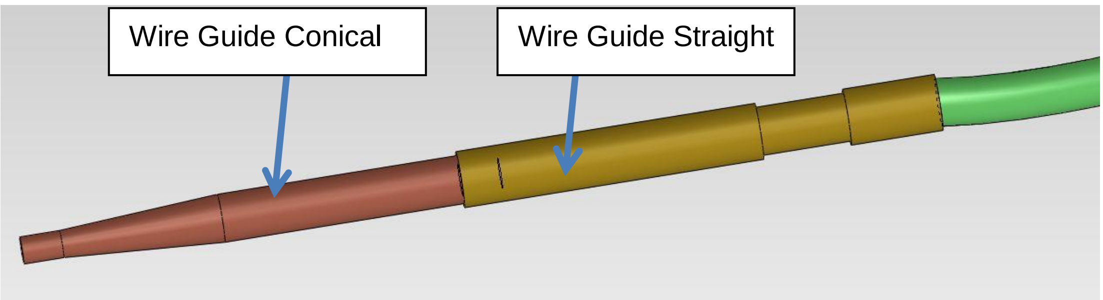


Figure 43: The picture shows the Wire Guide together with the plastic tube

7.8 Wire Feeder and Leveller

Both Wire Feeder and Leveller were decided to be standard components from ESAB. Standard interfaces of the engine was used to fasten it to the Arm by the help of a mounting plate (Mounting plate feeder) with a hole pattern in accordance with the Arm and the engine M10x1.5 threaded holes. It was important to fasten the Wire Feeder and Leveller to the Arm so that it moves with the Arm through the welding operation, this to avoid tension and slacking on the welding wire and plastic tube. To provide interface to the plastic tube, a wire connector was constructed. The wire connector is pinched using a standard ESAB clamp integrated in the Leveller. All Wire Feeder and Leveller components can be seen in figure 44.

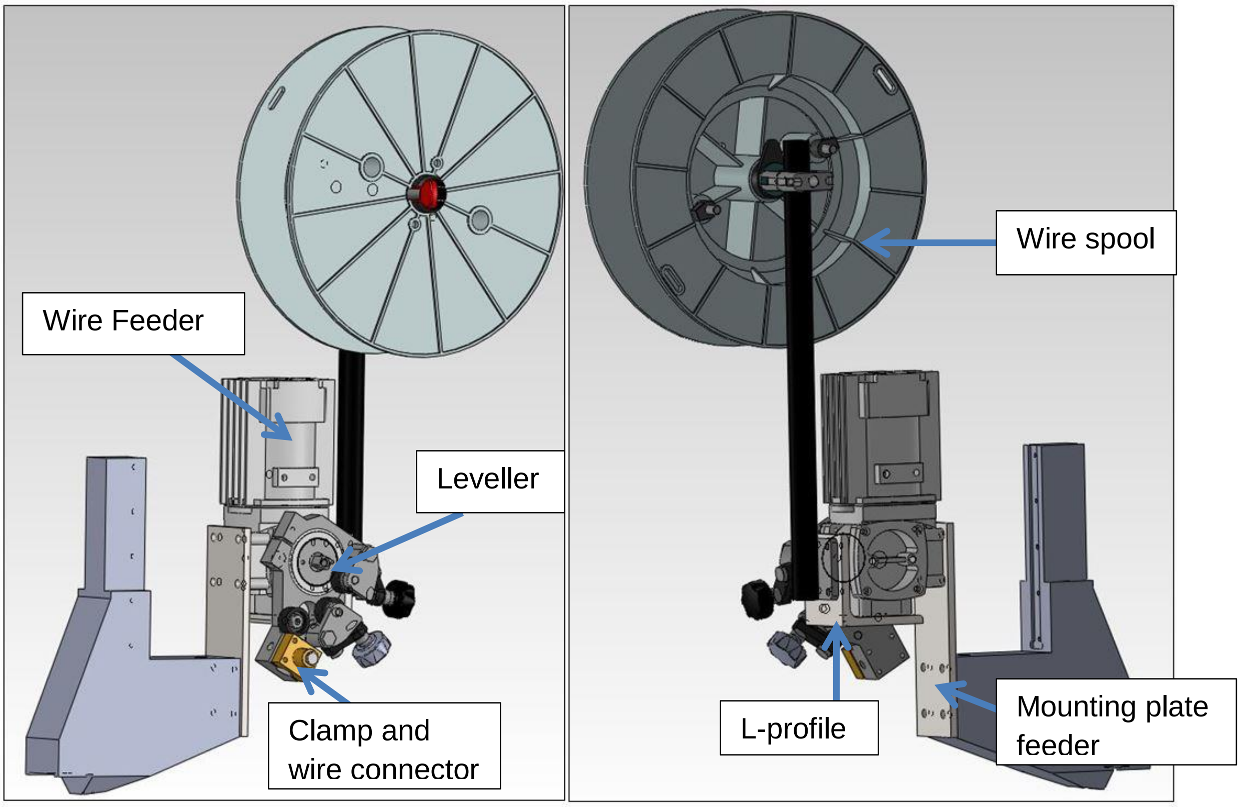


Figure 44: The pictures show the Wire Feeder and Leveller mounted on the arm

The engine and the wire spool are mounted vertically to yield a low torque at the Arm. An L-profile beam with M10x1.5 holes was constructed to enable the vertical mounting of the wire spool to the engine (see figure 44).

7.9 Overall concept

All sub concepts described above formed the overall concept. Through the development of the sub concepts an important aspect was how they interacted with each other. Many of the sub concepts have one or more dependencies to other sub concepts, this made it important to look at the overall concepts during the individual concept development and make trade-offs where it was needed. The overall concept can be seen in figure 45, the different sub concepts are visualized in the figure to show how they come together.

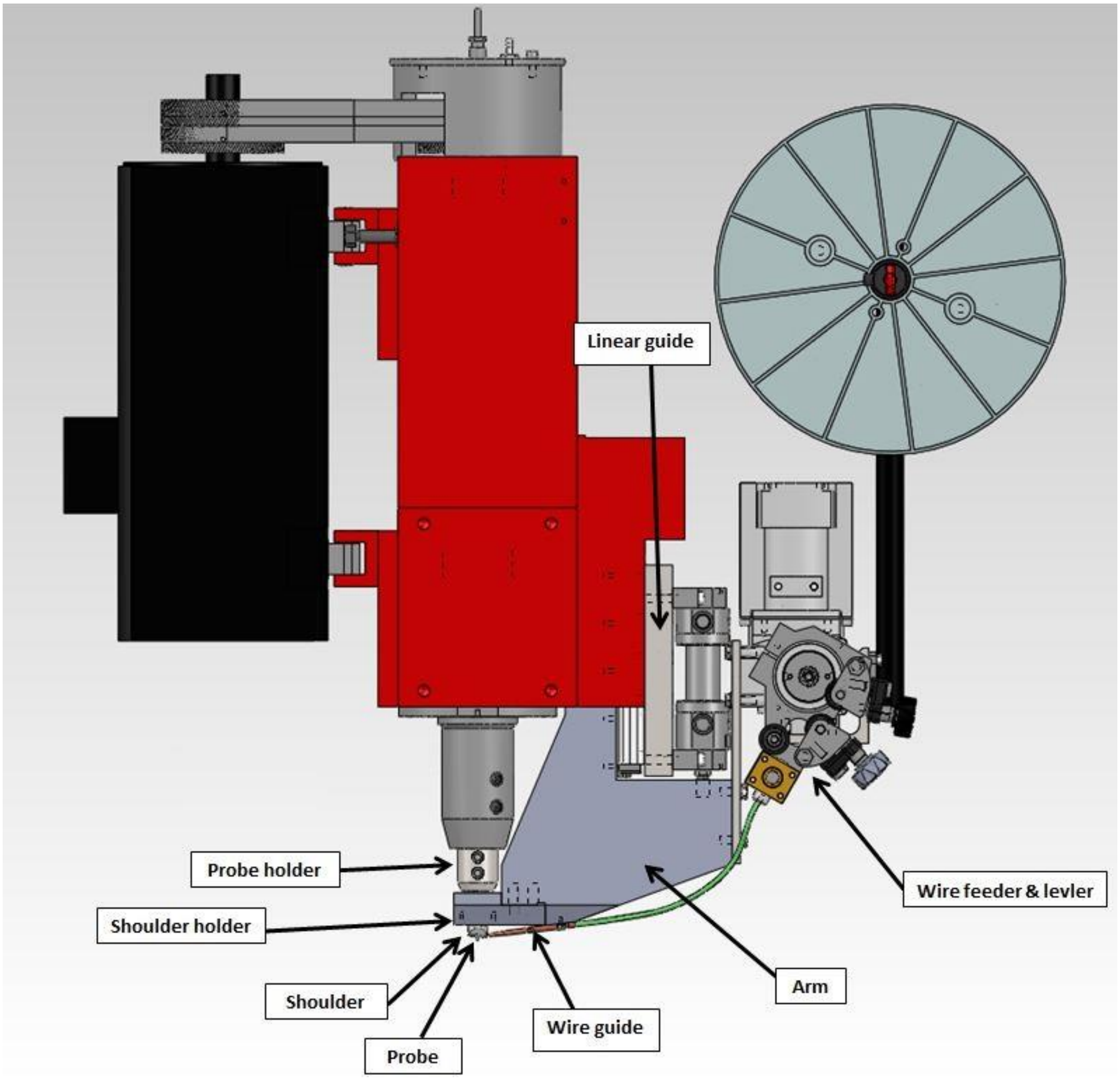


Figure 45: The overall concept on the lab machine

The objective of the construction was fairly broad with few limitations. There was however some preconditions and objectives that needed to be handled. Earlier in this chapter the different sub concepts and how they solve the different objectives and preconditions are described. In this chapter the main objectives are shortly repeated and the overall concept solution is visualized.

The concept was built around the current ESAB lab machine. The interface for the modules that moves separately from the lab machine was a flat surface in the front of the lab machine (see figure 47). The Probe and the Probe Holder needed to be connected to the spindle axis and incorporate the cooling pipe (see figure 46). These two packages needed to be aligned perfectly during welding when the Probe slides against the Shoulder.

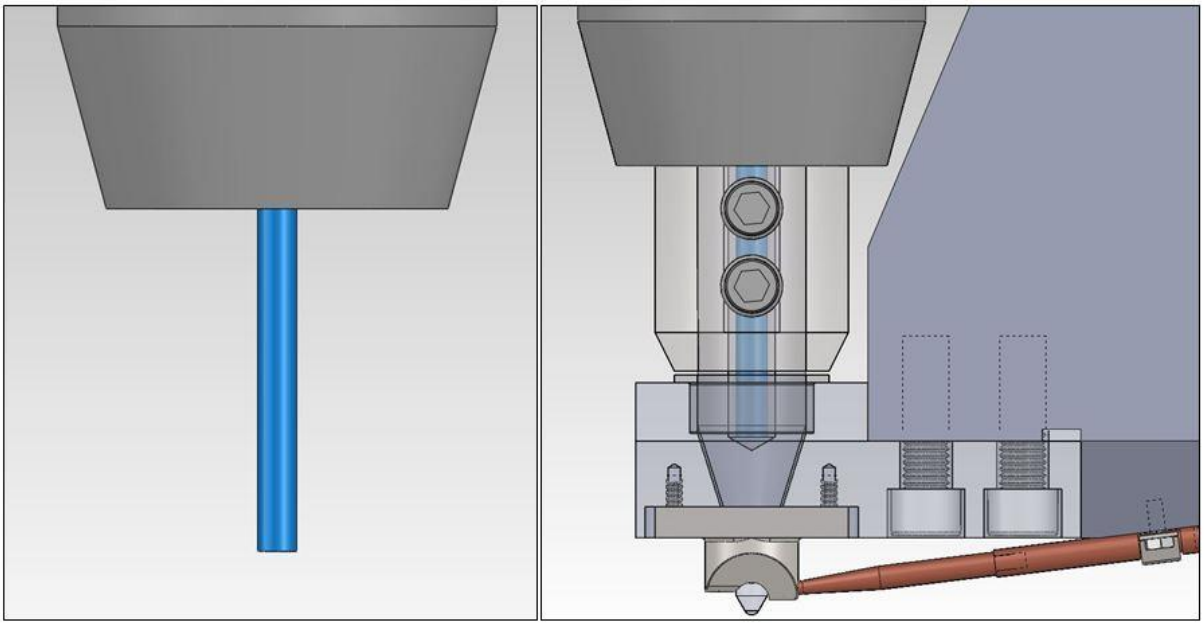


Figure 46: The picture to the left shows the cooling pipe and part of the spindle axis. The picture to the right shows the Probe, Probe Holder and Shoulder in transparent so the interfaces for the cooling pipe can be seen

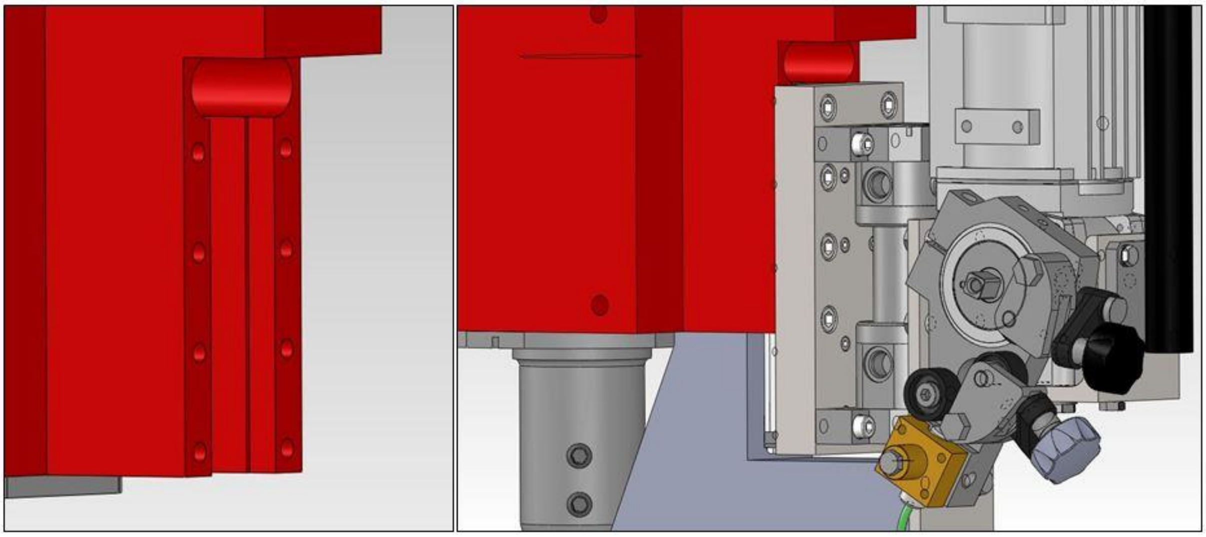


Figure 47: The picture to the left shows the mounting interface on the lab machine. The picture to the right shows how the whole concept is mounted to the lab machine via the mounting plate

The maximum horizontal deflection during welding was set to 0.2mm. To solve this, the construction needed to be robust. The horizontal deflection was constantly considered during the development and the final concept deflection was verified in ANSYS (see appendix A4). The deflection of the construction from the ANSYS simulation can be seen in figure 48.

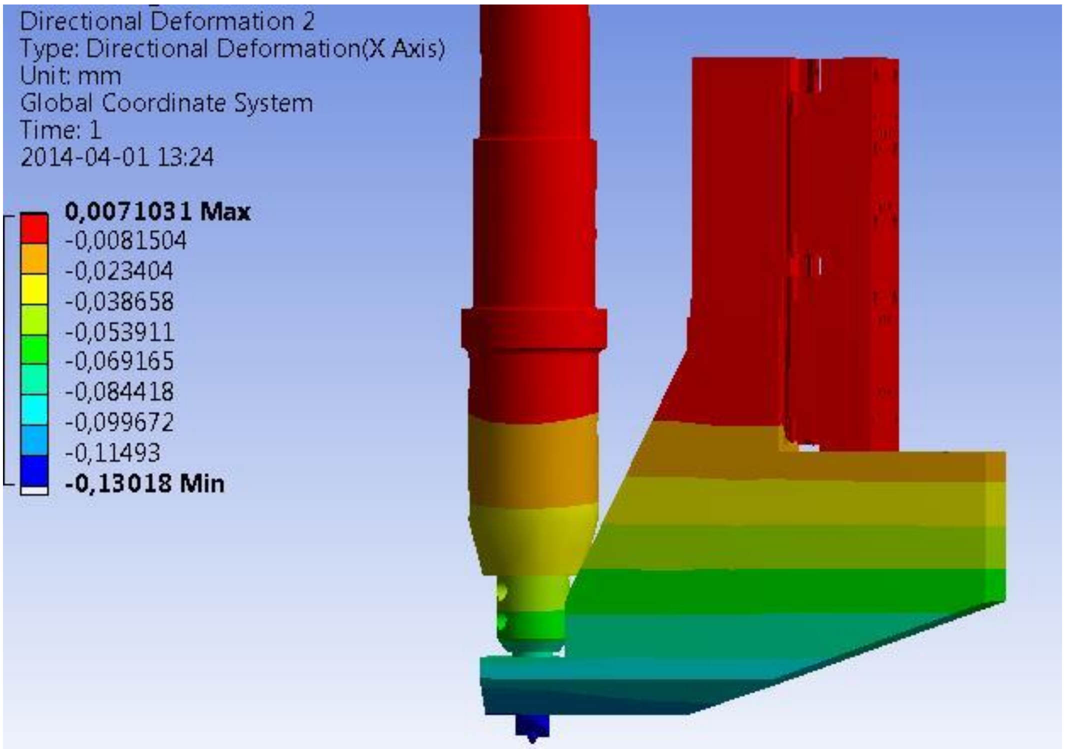


Figure 48: Horizontal deflection from ANSYS

The Shoulder needed to have an independent movement and pressure from the Probe. This was needed to be able to weld different material thicknesses as well as to be able to separate the Probe from the Shoulder to avoid adhesion. Figure 49 shows the overall concept in welding position and the concept at full hydraulic stroke. In figure 50 a detailed view of the Probe and Shoulder can be seen, both in welding position and when the Probe is separated from the Shoulder.

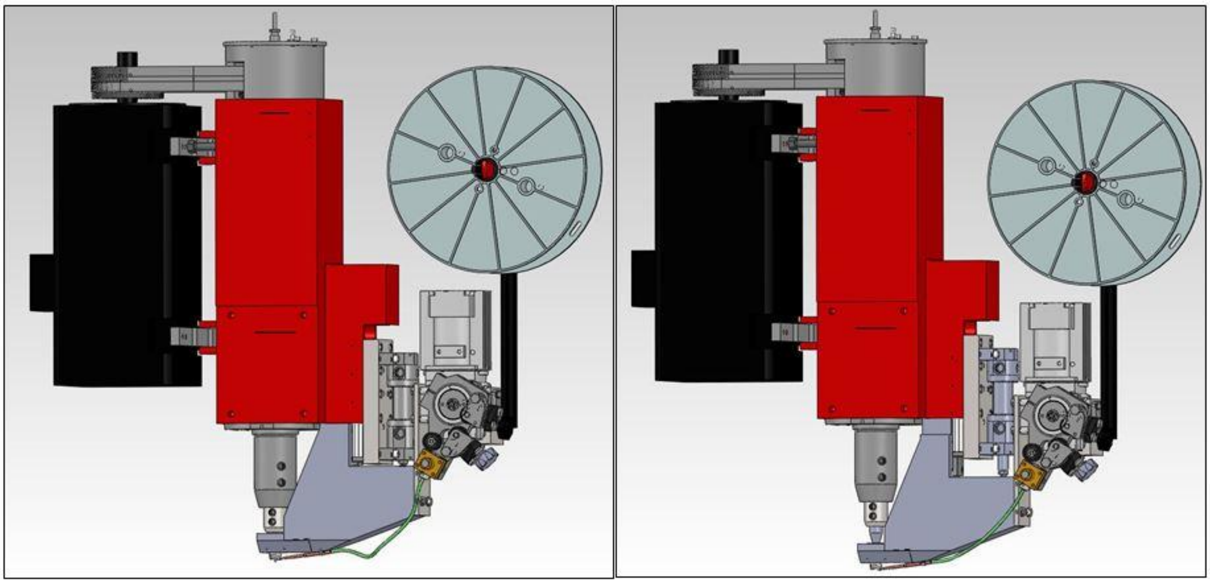


Figure 49: To the left is a 3D-view of the overall concept with no stroke on the hydraulic cylinder. The right pictures show the overall concept with full stroke on the hydraulic cylinder

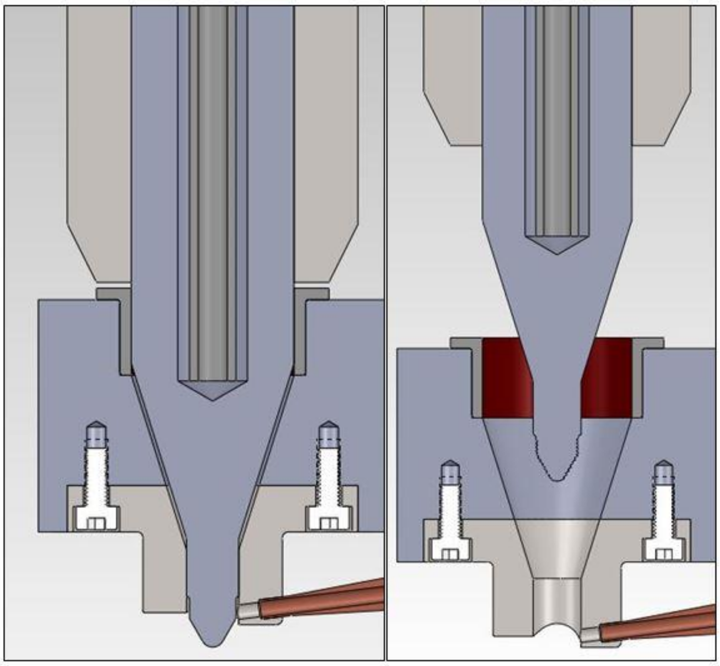


Figure 50: Both pictures show a cross section view of the Probe Holder, Probe, Shoulder Holder, Shoulder and bearing. The one on the left is with no stroke and the one on the right with full stroke on the hydraulic cylinder

The welding wire needed to be inserted directly to the Probe through the Shoulder with an angle. The Shoulder needed to have a sliding contact to the Probe and at the same time seal the welded material. All this needed to be incorporated within the 90 degree angle to avoid clashing into the weld piece. Figure 51 shows the Shoulder and the Wire Guide with a transparent weld piece.

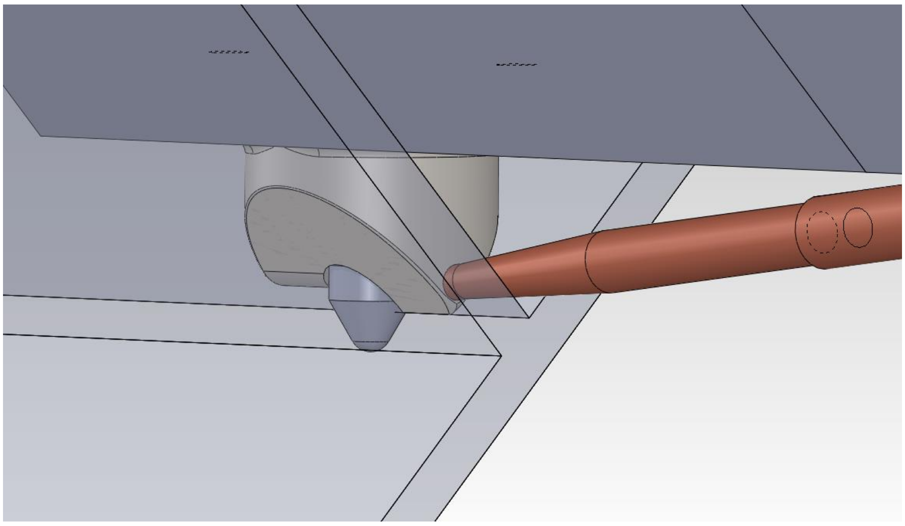


Figure 51: 3D-view of Shoulder Holder, Shoulder, Probe and Wire Guide together with the weld piece (transparent)

The interaction between the Probe, the Shoulder and the Shoulder Holder was an important interface design. The Probe needed to have a 0.5mm overlap of the two components of the weld piece. This had to be done while keeping a precise alignment to the Shoulder and Shoulder Holder. These components also needed to support the creation of the weld, which includes; heating and forcing the material to the weld zone, mixing the heated material and forming the weld fillet. Figure 52 shows the alignment between the Probe, Shoulder and Shoulder Holder. In figure 53 the forming of the weld fillet is illustrated.

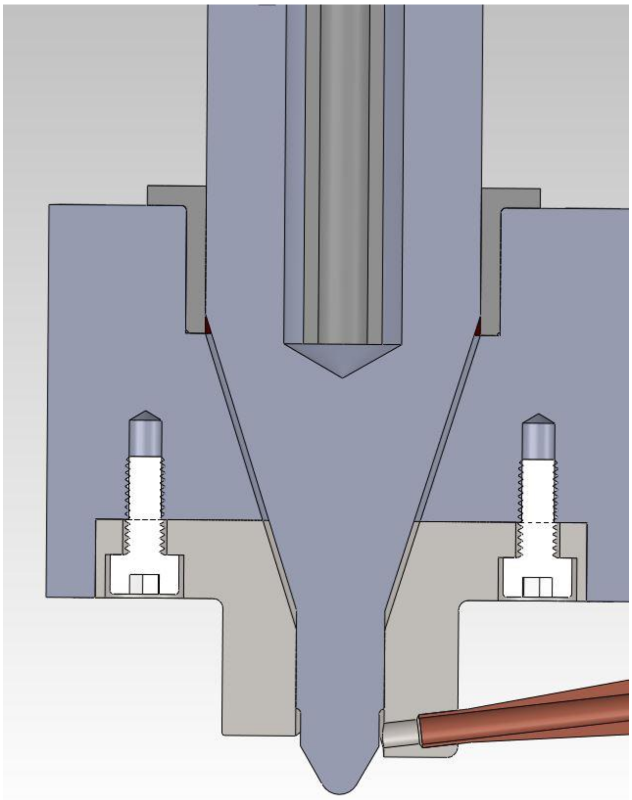


Figure 52: Cross section view of the Probe, Shoulder Holder, Shoulder and Wire Guide

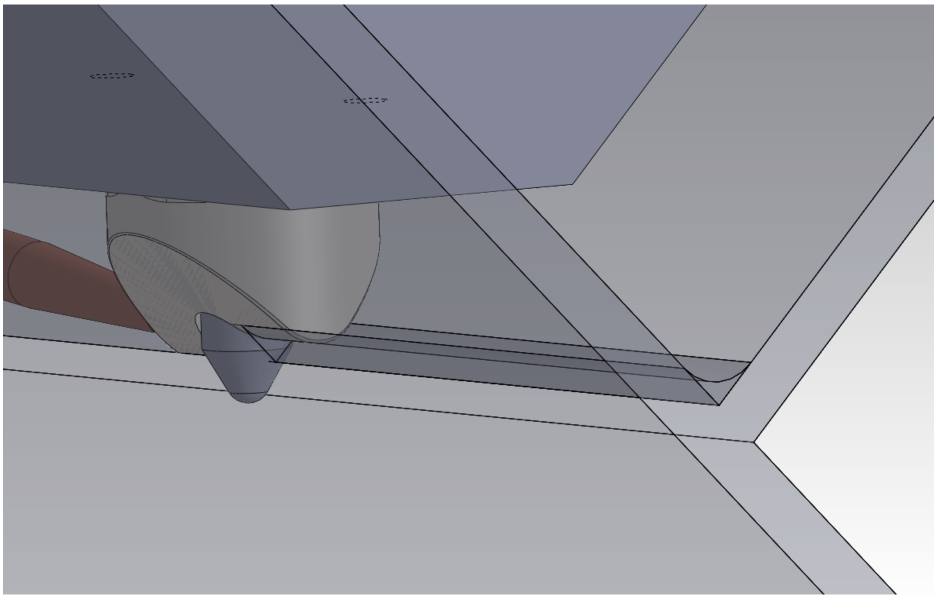


Figure 53: 3D-view of the Shoulder Holder, Shoulder, Probe and Wire Guide with a weld piece containing a created weld fillet

The developed concept needed to be modular. The Probe and Shoulder had to have easy replacement possibilities to be able to be changed if different material thicknesses would be welded. During the development it was also a consistent effort on preparing the construction for the cooling and the heating concepts. This enhanced the replacement requirements and was a big reason why the Shoulder Holder was made replaceable as well. Preparing for the heating and cooling concepts also affected design decisions regarding the size of components, this to be able to leave space for possible components that would be added in the Part 2 development. Figure 54 shows an exploded view of how the changeable components can be changed.

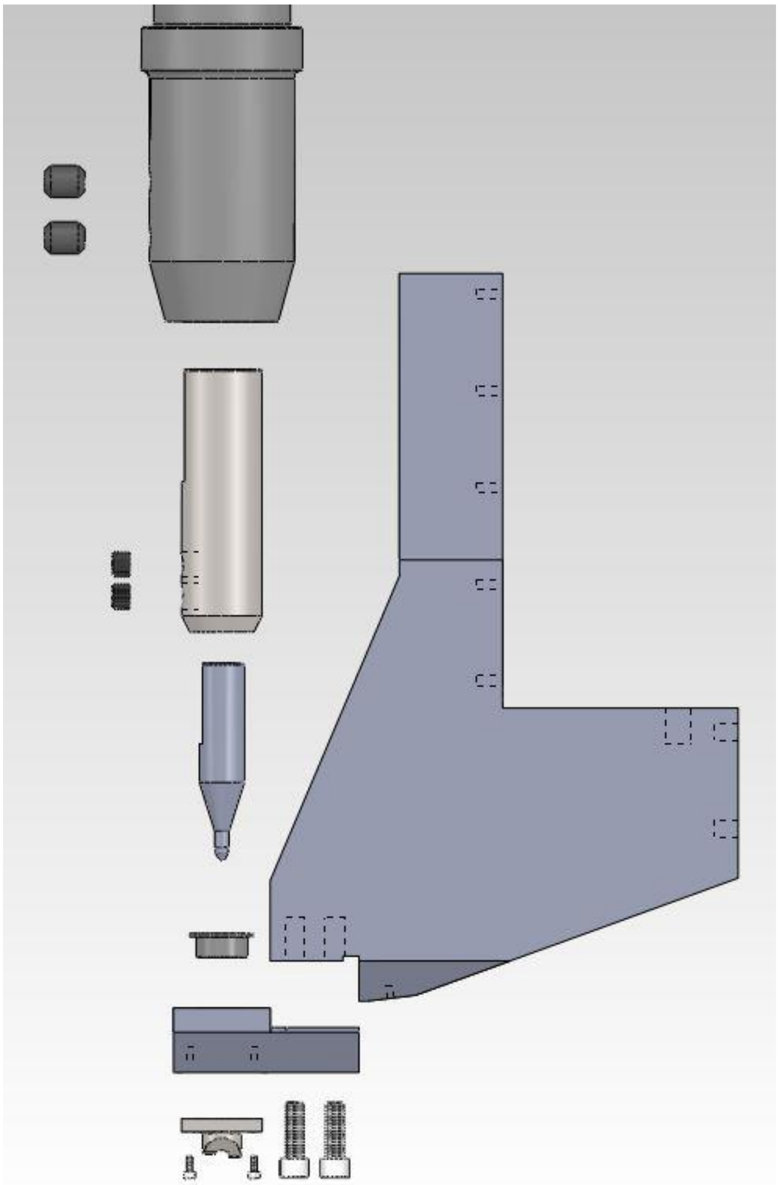


Figure 54: Exploded view of the welding components and their fastening elements

7.10 Welding of different material thicknesses

The main reason for adding replacement possibility to the Shoulder and the Probe was to enable welding of different material thicknesses without any major changes to the construction. The aim was to allow welding of different material thicknesses by only replacing the Probe and the Shoulder.

The driving factor to enable replacement was to keep the interface to the Shoulder Holder standard. This means that the angle of the cone and the upper cone diameter of the Shoulder had to be constant.

A Matlab script (see appendix C2) was developed to calculate the design changes needed for welding different material thicknesses. The Probe and the Shoulder were originally designed to ensure easy modification. Only a few measures of the Probe and the Shoulder had to be changed to enable welding of different material thickness. The Matlab script was generic, with input values of Probe diameter and material thickness. This would enable completely optional Probe diameters and material thicknesses to be tested. Using this script, with the generic Probe and Shoulder design, thus provides great design value during testing.

In table 1 examples of design parameters are listed, the Probe diameter and material thickness corresponds to the tests made by Company X. A drawing showing the table parameters is shown in figure 55. A Probe and a Shoulder were constructed for each set of parameters shown in table 1. A cross section view of their design can be seen in figure 56. All designs works with the general design of the overall concepts due to the standard interface between the Shoulder and the Shoulder Holder.

Table 1: Calculated Probe and Shoulder dimensions

No.	Material thickness(input) [mm]	Probe diameter(input) [mm] A	Straight length [mm] B	Contact length [mm] C	Probe tip radii [mm] D	Weld fillet [mm] E
1	1.6	6	1.4	7	1	1
2	4	8	3.1	9	2	4
3	8	10	6.4	11	3	5
4	12	12	9.7	13	3	5

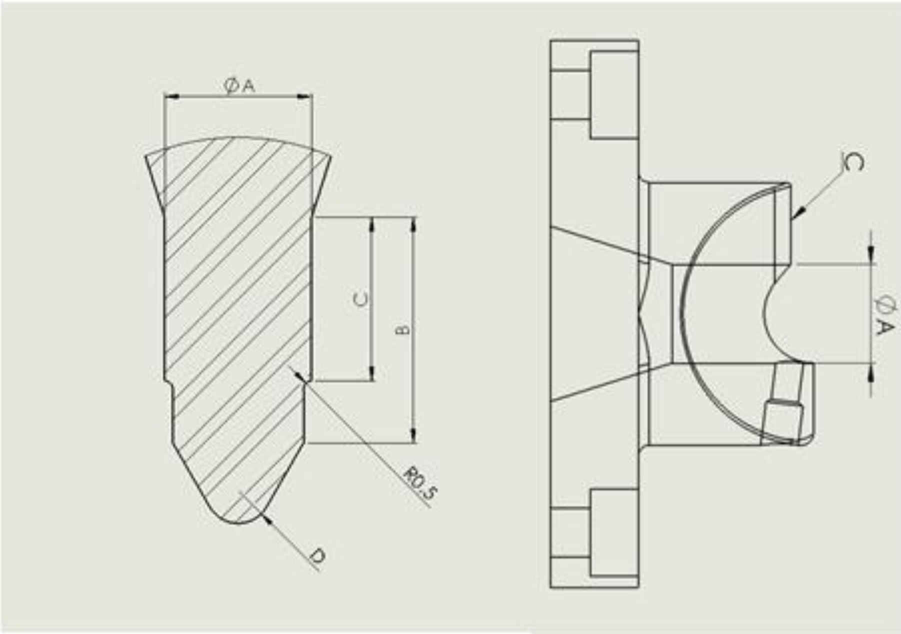


Figure 55: Design parameters for Probe and Shoulder

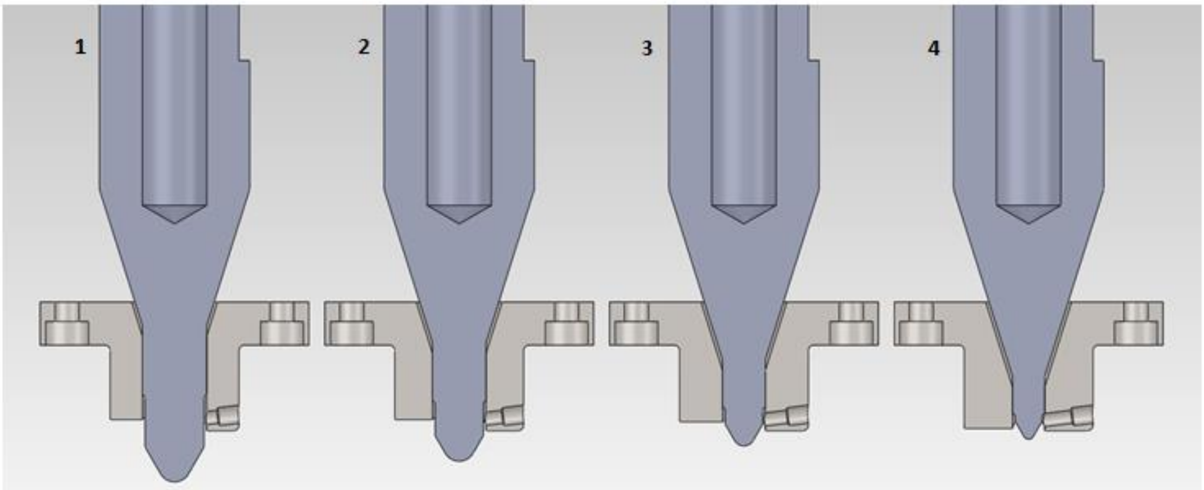


Figure 56: Cross section view of Probe and Shoulder for the parameters in table 1

8 Part 2 preconditions

The part 2 concept will be primarily based on the concept of part 1. The same Linear Guide, Arm, Wire Feeder and Leveller, Probe Holder and Probe as in the part 1 concept will be used in the part 2 concept as well. The Shoulder and Shoulder Holder are the modules that will be modified to incorporate a preheating of the weld piece and welding wire prior to the welding operation, as well as a cooling of the weld piece after the welding operation.

Since the Arm from part 1 will be used, the interface for the Shoulder Holder are set to be the same milled rail with two M12 screws as in the part 1 objective. The Shoulder and the Shoulder Holder will also have the same lathed geometry interface for the Probe as in part 1. These preconditions are set as a request from ESAB to be able to use as many parts as possible from the part 1 concept.

The cooling function of the part 2 concept will use the same water pump system as in the Probe cooling system available at the lab machine. This was also a precondition from ESAB to be able to make as few changes as possible to the current lab machine. The water pump is a 12V pump with a nominal pressure of 100MPa and a volume flow of 7l/min (TECH Products Sweden AB, 2014). The objective of the cooling function is to cool the weld piece as fast as possible to avoid residual stresses in the weld piece.

The heating function is more open, with restrictions only from the geometry of the part 1 concept and the lab machine. The objective of the pre heating is to enable the Probe to heat the weld piece and the welding wire to forging temperature faster. This would enable a faster welding operation. The weld piece and the welding wire shall be heated to a temperature near 300^{o}C, but must not be heated above 300^{o}C; this is to avoid cladding of the welding wire and damaging of the weld piece.

During the welding operation the Probe heats up the weld piece to forging temperature. This will affect the heating and cooling concept of the part 2 development. The temperature at the weld zone is estimated to 500^{o}C by ESAB.

The same weld piece and lab machine preconditions as in part1, described under general preconditions, are also applied in the part 2 development.

9 Concept generation Part 2

The development of part 2 of the project had the goal of finding a working solutions for preheating the weld piece and the welding wire, and cooling of the weld piece. To assist the cooling and the heating functions, an insulation function was identified. The insulation would hinder the heat from moving from the heated to the cooled side of the Shoulder, thus enhancing both heating and cooling capabilities.

Since the Shoulder was the only module in contact with the weld piece and the welding wire it was quickly discovered that it would work as the main module for heating, cooling and insulation. The Shoulder Holder would then work as a complement, adapting to, and assisting the Shoulder to perform its functions.

A detailed brainstorming together with an ample research was performed to identify the best possible solutions. These were narrowed down until a couple concepts remained for all functions. These concepts are described in this chapter.

9.1 Cooling

The cooling function had, as mentioned before, a restriction to use water as coolant. Since the cooling is applied after the weld zone, there were no restrictions on prolonging the Shoulder and Shoulder Holder in the cooling direction. The concepts were only limited by the weld piece 90 degree angle and the Probe interface on the Shoulder and Shoulder Holder. The challenge was to cool the weld piece as fast as possible to avoid heat transfer and the resulting residual stresses in the weld piece. The three most promising concepts are listed below.

9.1.1 Tube Cooling Pipe

Two cooling concepts containing a water flow through the Shoulder and the Shoulder Holder were identified. In these concepts the heat is transferred from the weld piece to the Shoulder. The Shoulder is then cooled by the flowing water. The critical cooling area of the Shoulder is in the radii just above the weld fillet. This is where the welding material will have the highest temperature and also where the largest heat transfer between the Shoulder and the weld piece will take place. Due to this, both tube cooling concepts have a hole through the radii of the Shoulder to perform the main part of the heat removal.

The Cooling Pipe concept has a water inlet guide from the pump directly to the fillet of the Shoulder. The water is then guided through the Shoulder and up to the Shoulder Holder close to the actual welding area. The Shoulder Holder provides a horizontal guide to a water hose and onwards to the pump, thus creating a circulating system.

This concept enables a long cooling contact between the Shoulder and the weld piece. There might however be complications in fitting a hose connector so close to the weld piece. In figure 57 the cooling Pipe concept is shown. An angled pipe on the Shoulder is a possible way of enable fitting of the water hose to the Shoulder.

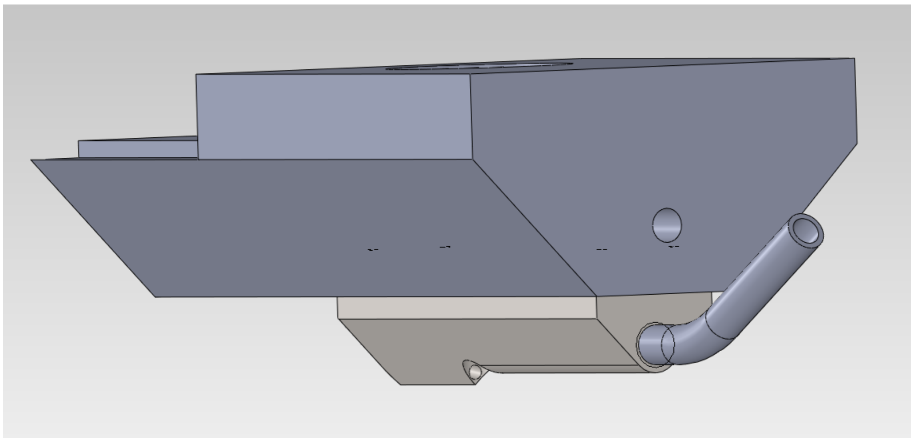


Figure 57: 3D-view of the Cooling Pipe concept

9.1.2 Tube Cooling Plug

The Cooling Plug concept (see figure 58) has a similar drilled horizontal hole in the Shoulder as in the Cooling Pipe concept. In this concept the hole is plugged and both the water inlet and outlet are placed on the Shoulder Holder. Two vertical holes connect the water inlet and outlet in the Shoulder Holder to the horizontal hole in the Shoulder.

This concept would solve the space issue of the hose connector from the Cooling Pipe concept. It could however result in inferior cooling due to shorter cooling length in the Shoulder due to the plug.

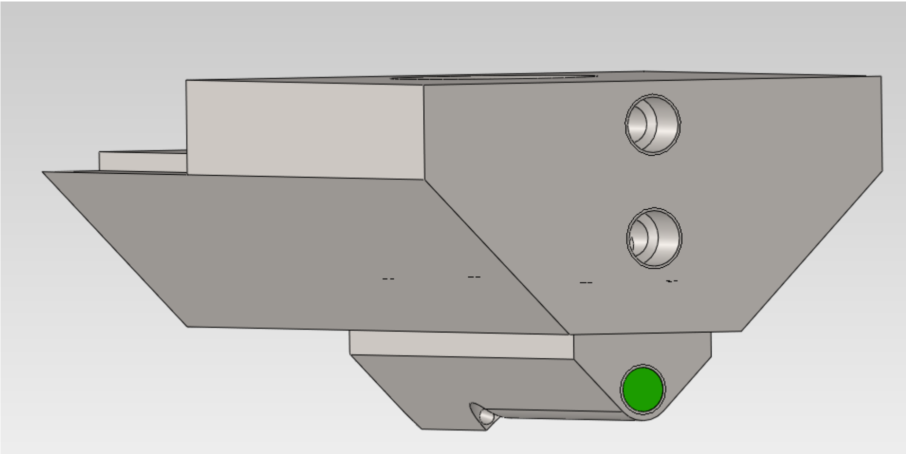


Figure 58: 3D-view of the Cooling Plug concept

9.1.3 Evaporating Water

The Evaporating Water concept (see figure 59) has a nozzle situated directly after the Shoulder. Water is sprayed out of the nozzle on the weld piece to perform the cooling operation. The sprayed water needs to evaporate completely since no residual water is allowed on the weld piece or in the welding environment.

This concept would provide a very large heat removal, this is due to the fact that the heat transfer coefficient is enlarged when the water changes phase. A negative aspect is that the water does not complete a circulating system. This means that the pump needs to be refilled. Another aspect is that the water is applied after the Shoulder. This means that the weld piece cannot be cooled until the Shoulder has completely passed the weld zone.

Figure 59: Evaporating Water concept

9.2 Heating

The heating concepts were heavily restricted by the geometry of the part 1 concept. There was a limited possibility to extend the Shoulder and Shoulder Holder in the welding direction since the Arm was fixed. This left very little space for the heating and narrowed down the possible solutions greatly. However, there were no restrictions in the mechanism of producing heat. After the initial screening, three concepts remained.

9.2.1 Tubular Heat Element

This concept involves heating the Shoulder by a heating media flowing through a pipe and a circular path through the front of the Shoulder (see figure 60). The heating media could be air, steam or a liquid metal depending on the applicability and heating effect. This would heat the front of the Shoulder and by that also heating the weld piece that the Shoulder is in contact with and the welding wire that is fed through the Shoulder.

This concept could provide a good heating and provide a possibility to regulate the heating by regulating the flow rate of the heating media. It could have fitting implications since there is very little space in the front part of the Shoulder.

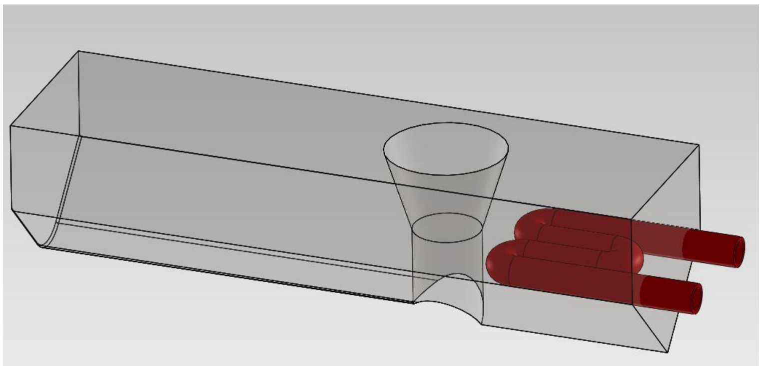


Figure 60: 3D-view of the Tubular Heat Element concept

9.2.2 Cartridge Heater

The cartridge heater (see figure 61) uses conducting resistance wires enclosed in metal housing to create heat. The cartridge heater is placed in a hole in the front of the Shoulder above the inlet of the welding wire. This would heat the front part of the Shoulder and by that also the wire and the weld piece in contact with the Shoulder.

This concept has less space issues since cartridge heaters are available in small sizes. It could however result in an insufficient heating if the power output is too low.

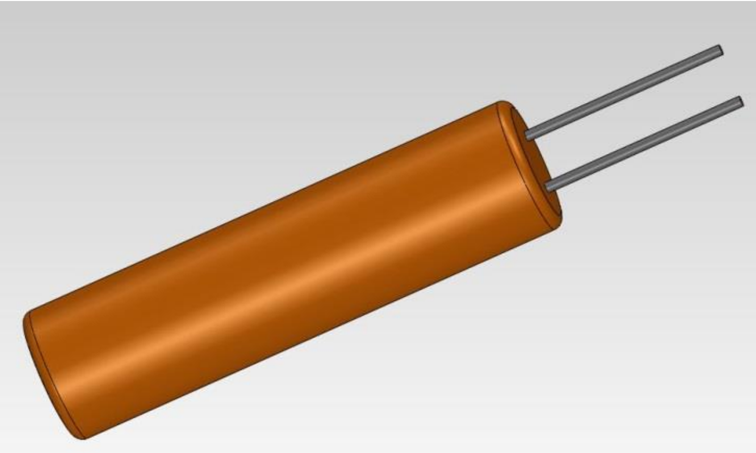


Figure 61: 3D-view of the Cartridge Heater concept

9.2.3 Heating Cables

Heating cables are insulated conducting cables that are heated by an electrical current. The heating cables would be wrapped around the Wire Guide to provide heating of the wire. The cables would also be fitted in a drilled path in the front part of the Shoulder and by that heating the Shoulder and the weld piece as seen in figure 62.

This concept has the advantage of both heating the Shoulder and the Wire Guide, thus providing a larger heating power to the welding wire. There could however be more problematic in providing enough heating to the Shoulder since the heating cables does not have large power. There could also be implications in machining the path in the Shoulder for the heating cables.

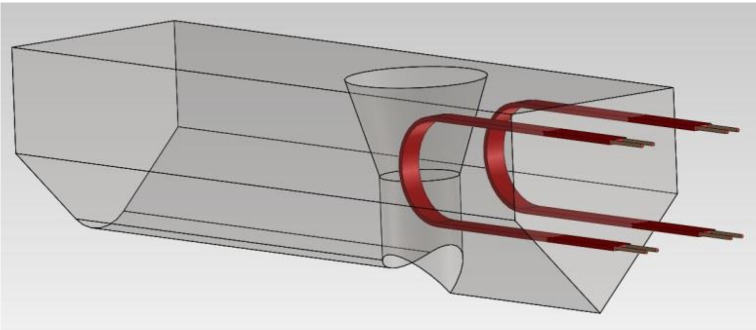


Figure 62: 3D-view of the Heating Cables concept

9.2.4 Insulation

Since the Shoulder would be the element of both heating and cooling the insulation was set to be placed inside the Shoulder. The insulation was restricted not to interfere with the conical hole of the Shoulder.

9.2.5 Small Plate

The Small Plate concept (see figure 63) has a thin plate of stainless steel as insulating media. The plate is situated on the cooling side of conical hole in the Shoulder. This concept lets the heat from the weld zone heat the front of the Shoulder while still keeping the cold side insulated.

The challenge with this concept is to machine the interface for the insulation plate in the Shoulder. The insulation will also take up space, and this might interfere with the cooling function.

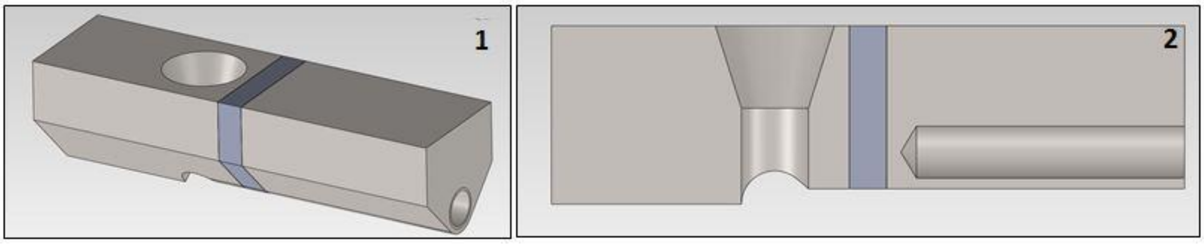


Figure 63: 1) 3D-view of the Small Plate concept. 2) Cross section view of the Small Plate concept

9.2.6 No Insulation

Due to the machining implications of the Small Plate concept, a concept with no insulation was considered. The negative aspect is that the heat from weld zone and the heating concept can fairly easily transfer to the cooled side of the Shoulder. This needs to be weighed against the fact that the machining would be easier. The lack of an insulation plate might also provide a better cooling function since more space will be available in the Shoulder for cooling.

10 Concept selection Part 2

Unlike the part 1 concept, the part 2 concept would not result in a working prototype. The fact that no prototype would be built of the concept during the time of the project did not change the concept selection procedure for the part 2 concepts. All parts had to work and all parts had to be ready for a prototype build if ESAB would want to test it in the future.

10.1 Cooling

The tube cooling concepts, Cooling Pipe and Cooling Plug, were evaluated against the Evaporating Water concept through feasibility. After investigation of the pump system used at the lab machine it was discovered that the system did not support a refilling operation and could only be used as a circulating system. Consequently the Evaporating Water concept was disregarded.

The tube cooling concepts were then evaluated through their cooling capability. This was done through thermal analysis in ANSYS. An important aspect of the water cooling was the convection capability of the flowing water. The convection is automatically calculated in ANSYS by Newton's law of cooling (equation 1). The input for the analysis is the heat transfer coefficient. The heat transfer coefficient is a function of the water flow, water properties and some dimensionless parameters. The heat transfer coefficient for this application was determined by equation 12.

$$h = heat\ transfer\ coefficient\ [W/m^2K]\ (wanted)$$

$$Dimaeter\ of\ cooling\ path$$
$$D = 6 * 10^{-3}\ [m]$$

$Water\ flow\ from\ water\ pump$ (TECH Products Sweden AB, 2014):
$$v_f = 7\ [l/min]$$

$$v = \frac{\frac{\frac{v_f}{100}}{60}}{\pi D^2 * \frac{1}{4}} = \frac{\frac{\frac{7}{100}}{60}}{\pi * 6 * 10^{-3^2} * \frac{1}{4}} = 4.13\ [m/s]$$

$\rho = density = 998\ [kg/m^3]$ (White, 2011)
$\mu = visocity = 1 * 10^{-3}\ [kg/(m * s)]$ (White, 2011)
$C = specific\ heat = 4181\ [J * K/kg]$ (Yunus A. Cengel, 2007)
$K = thermal\ conductivity = 0.613\ [W/(m * K)]$ (Yunus A. Cengel, 2007)
$f = Darcy\ friction\ factor$
$Nu = Nusslet\ number$
$Re = Reynolds\ number$
$Pr = Prandtl\ number$

$Nusslet\ number$ (University of Minnesota, 2014):
$$Nu = \frac{h * D}{K} \tag{5}$$
$$h\ can\ be\ solved\ from\ equation\ 5$$
$$h = \frac{Nu * K}{D} \tag{6}$$

$Nu\ according\ to\ Gnielinski\ correlation$ (University of Minnesota, 2014):

$$Nu = \frac{f/_8 * (Re - 1000) * Pr}{1 + 12.7 * \sqrt{f/_8} * (Pr^{\frac{2}{3}} - 1)} \tag{7}$$

$Calculation\ of\ Re$ (White, 2011):

$$Re = \frac{\rho * v * D}{\mu} = \frac{998 * 4.13 * 6 * 10^{-3}}{1 * 10^{-3}} = 24708 \tag{8}$$

$Calculation\ of\ f$ (White, 2011):

$$f = (1.8 * \log\frac{Re}{6.9})^{-2} = (1.8 * \log\frac{29940}{6.9})^{-2} = 0.0244 \tag{9}$$

$Calculation\ of\ Pr$ (White, 2011):

$$Pr = \frac{\mu * C}{K} = \frac{1 * 10^{-3} * 4148}{0.613} = 0.7 \tag{10}$$

$Nu\ can\ now\ be\ calculated\ from\ equation\ 7\ with\ the\ values\ from\ 8, 9\ and\ 10$:

$$Nu = \frac{f/_8 * (Re - 1000) * Pr}{1 + 12.7 * \sqrt{f/_8} * (Pr^{\frac{2}{3}} - 1)} = \frac{0.023/_8 * (29940 - 1000) * 0.7}{1 + 12.7 * \sqrt{0.023/_8} * (0.7^{\frac{2}{3}} - 1)} = 175 \tag{11}$$

$h\ can\ now\ be\ calculated\ with\ the\ value\ from\ equation\ 11\ with\ help\ of\ eqation\ 6$

$$h = \frac{Nu * K}{D} = \frac{175 * 0.613}{6 * 10^{-3}} = 17878\ W/(m^2 * K) \tag{12}$$

As shown in figure 64 the cooling capability was close to identical for the two concepts. The distance from the weld zone to the completely cooled area was 9.9 mm for both concepts. The Cooling Plug concept had a little wider cooling area at the back of the Shoulder, this can be explained by the extra vertical inlet hole of the Cooling Plug concept. The extra cooling at the edge for the Cooling Pipe concept made no difference since the Shoulder was cooled to the water temperature at the back for both concepts. The analyses in full are shown in appendix A5.

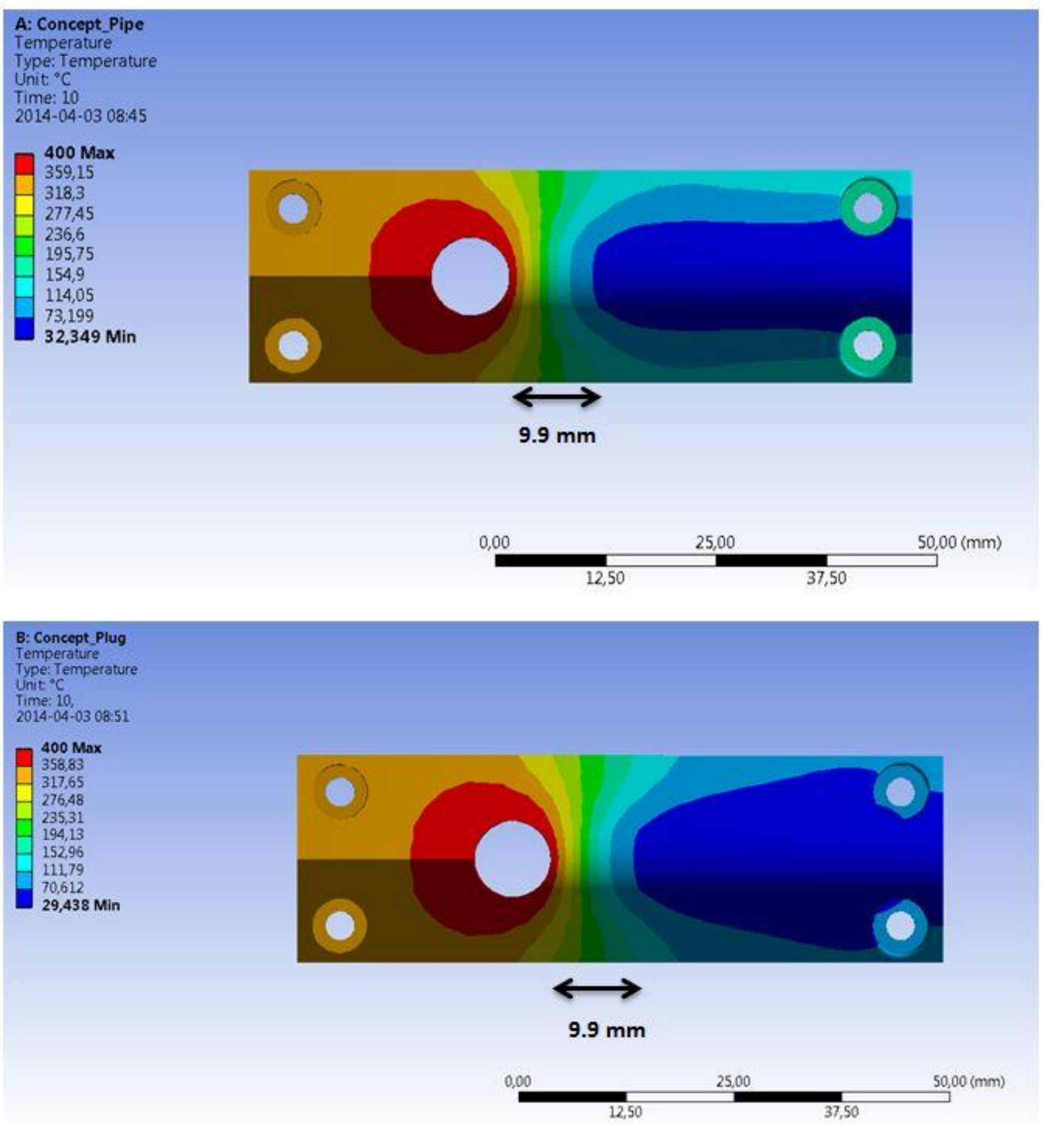


Figure 64: Shoulder cooling test of Cooling Pipe" (top) and Cooling Plug (bottom) concepts

The concept selection for the cooling concept was instead based on manufacturability. Through investigation of connection possibilities from the Shoulder to the hose of the pump it was discovered that the Cooling Pipe concept would provide insufficient space for a water connector. This could be solved by a two-step connection from the Shoulder. But since the Cooling Plug concept could support standard issue water connectors (see figure 65), that concept was chosen.

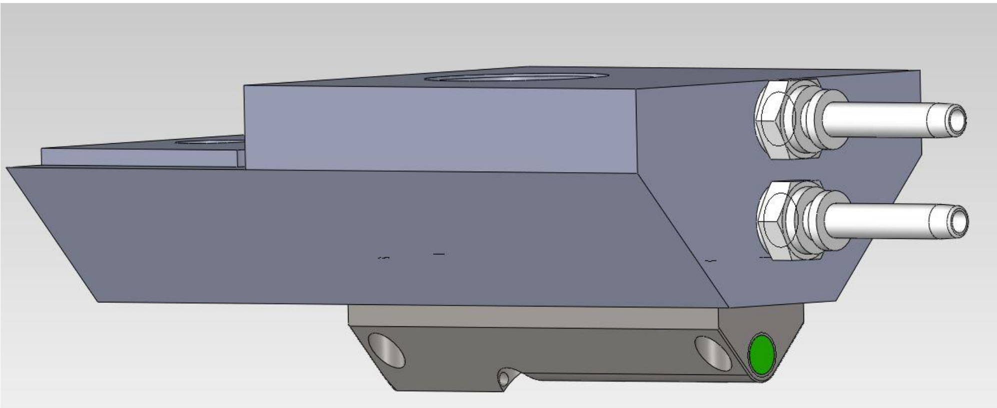


Figure 65: 3D-view of the Cooling Plug concept

10.2 Heating

The heating concepts were initially investigated through their abilities to meet the geometrical demands. This was since no alteration to the Arm or the front of the Shoulder Holder could be made. As shown in figure 66, the front of the Shoulder could be enlarged to the edge of the Shoulder Holder while still accommodating the geometrical demands. While this gave some extra space, it proved to be insufficient for the Tubular Heat Element concept. Hence that concept was disregarded.

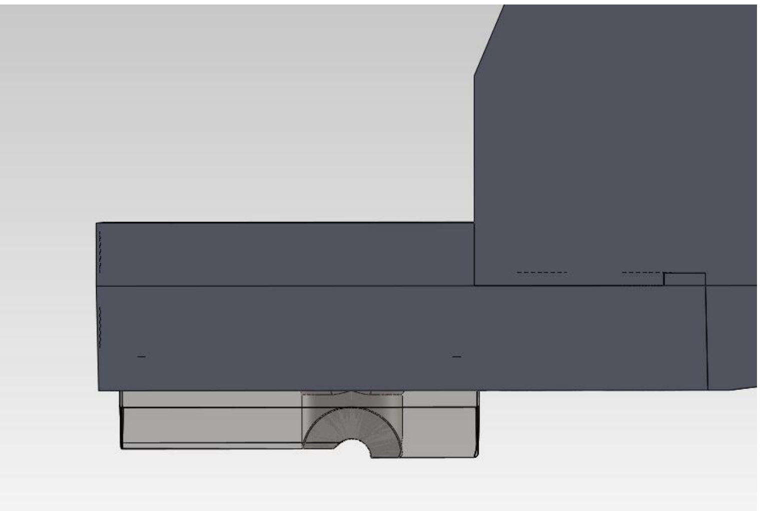


Figure 66: The picture shows both the Shoulder from part 1 and the Shoulder for part 2 mounted on the Shoulder Holder. The Shoulder from part 1 is the smaller one in in metal grey colour and the Shoulder from part 2 is the larger one in transparent

For the Cartridge Heater and Heat Cables concepts the feasibility was investigated through their ability to heat the welding wire and weld piece and their geometrical capabilities. Available standard issue components were investigated with focus on their power and size.

The fact that the welding area is constantly warm made it difficult to perform any realistic ANSYS analysis. It was hard to assess the amount of power needed since the weld zone would heat up the Shoulder and the weld piece close to the weld zone. Instead calculations were made to discover the amount of power that could be supplied by the components in the small space that was available.

From the calculations it was discovered that the heat cables would provide insufficient power to heat the weld piece and the welding wire. The cartridge heater had a much higher power output. The power that could be fitted in the Shoulder was 4.5W for the heating cables and 175W for the cartridge heater. The Cartridge Heater concept was therefore chosen as the heating concept. The calculations can be seen in appendix B.

10.3 Insulation

The main aspect of the insulation function was the cooling capability of the Shoulder close to the weld zone heat source. A test had to be made to discover if the reduced heat transfer from the Small Plate concept would provide a superior cooling over a regular setup with no insulation plate. The reason why this had to be tested was because the No Insulation concept would let the water cooling path be closer to the weld zone heat source as seen in figure 67.

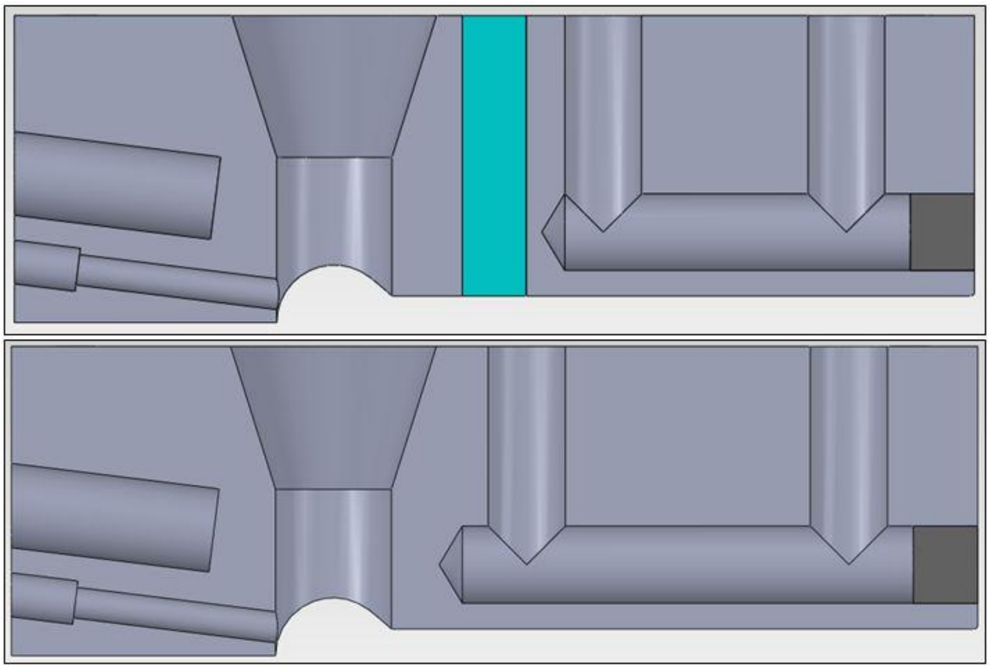
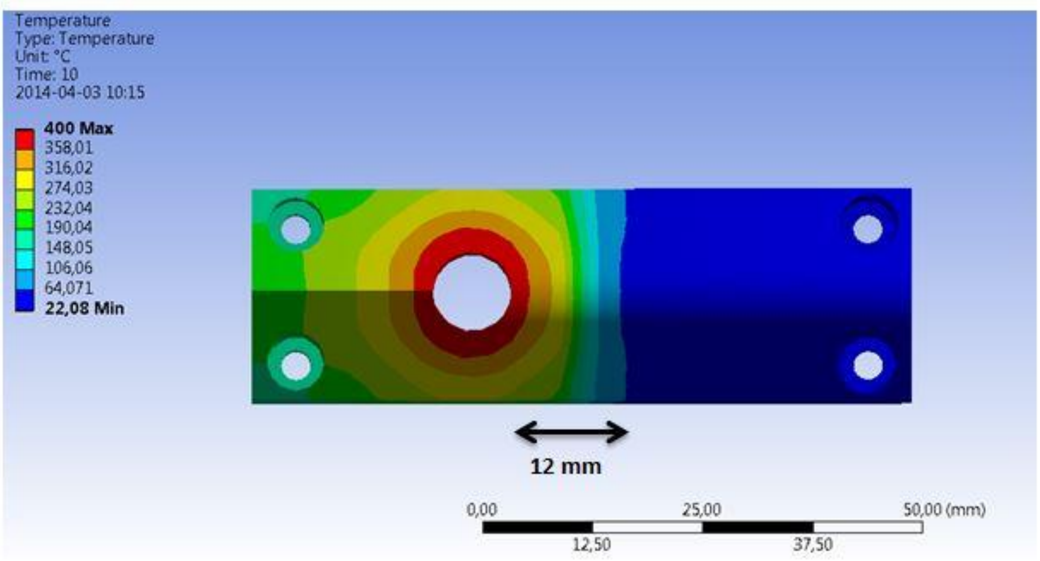


Figure 67: The picture shows that the horizontal cooling hole for the Shoulder without insulation (bottom picture) is longer than the cooling hole for the Shoulder with insulation (top picture)

Consequently, an ANSYS thermal analysis was set up to discover if the enlarged water convection from a longer path would result in a lower temperature compared to an insulation plate with lowered heat transfer from the weld zone heat source (see appendix A6). As seen in figure 68 the No Insulation concept had a lower temperature close to the weld zone. This combined with the fact that an insulation plate would make the Shoulder more complex, led to the fact that No Insulation was the chosen concept.



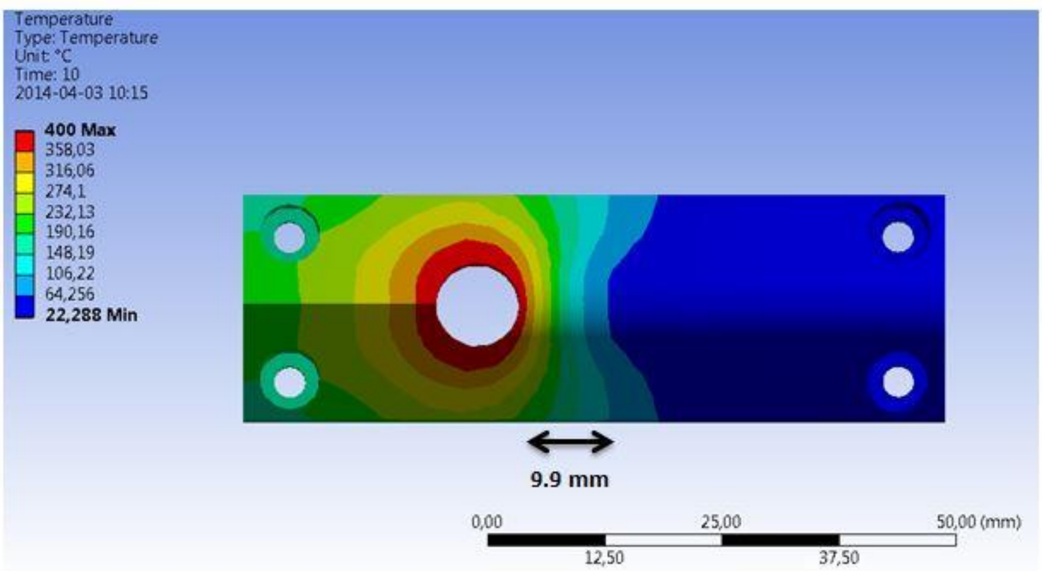


Figure 68: Shoulder fillet temperature of the Insulation Plate (top) and the No Insulation Concept (bottom). The shown distances in the figure are the distance from the weld zone to the part where the Shoulder is cooled to water temperature

11 Final concept part 2

The development of part 2 included preheating of the welding wire and the weld piece. Part 2 also included cooling of the weld piece with help of the existing water cooling system on the lab machine. The preheating and cooling had to be done without changing any main parts, except the Shoulder and the Shoulder Holder according to the preconditions. The development was done in consultation with ESAB and the suppliers of the sourced parts. All drawings can be found in appendix D2, all measures have been blurred due to confidentiality. The measures stated in this chapter have also been slightly altered.

11.1 Cooling

To be able to fit the heating and cooling concepts into the Shoulder some design changes had to be made on the Shoulder and Shoulder Holder from the part 1 concept. The cone dimensions and the radii for creating the fillet were kept, so the same Probe could be used and the 5mm fillet could be made. The Shoulder was extended opposite the welding direction to allow longer cooling contact. The Shoulder was also extended in the welding direction to allow fitting of the heating elements. The mounting holes of the Shoulder and Shoulder Holder were changed to allow the interface of the cooling pipe. Instead of being centred, the holes were moved to the side of the Shoulder, this allowed the water path to be in the centre of the Shoulder (see figure 69). This change also supported the geometrical changes of the Shoulder and Shoulder Holder for the heating concept, which also needed space in the centre of the Shoulder.

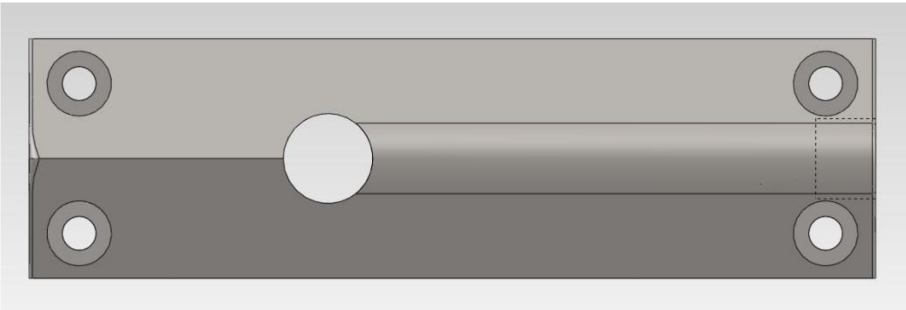


Figure 69: 3D-view of the Shoulder for the part 2 concept

The cooling of the Shoulder was performed by letting water circulate through the back of the Shoulder. To enable the water to circulate through the Shoulder three holes had to be made. One hole parallel to the radii on the Shoulder, this was a 48mm M8 hole with an 8mm thread. Two 6mm holes was also made, these were drilled from the top of the Shoulder intersecting the M8 hole. The cooling hole closest to the conical hole for the Probe had the same angle as the cone itself, this to enable cooling as close to the weld zone as possible. The hole parallel to the radii was sealed with a M8 conical plug. The inlet and outlet for the water were made with hose nipples, fitted on the Shoulder Holder. The hose nipples had 1/8” interface to the water hose and a G1/8 thread interface to the Shoulder Holder. The G1/8 holes were extended with a 6mm drill to align with the vertical holes of the Shoulder. One angled and one vertical 6mm hole was then drilled from the bottom of the Shoulder Holder to match the holes in the Shoulder. To prevent water leakage between the Shoulder and the Shoulder Holder, interfaces for O-rings on the angled and vertical hole were machined on the Shoulder. A cross section of the Shoulder and Shoulder Holder can be seen in figure 70.

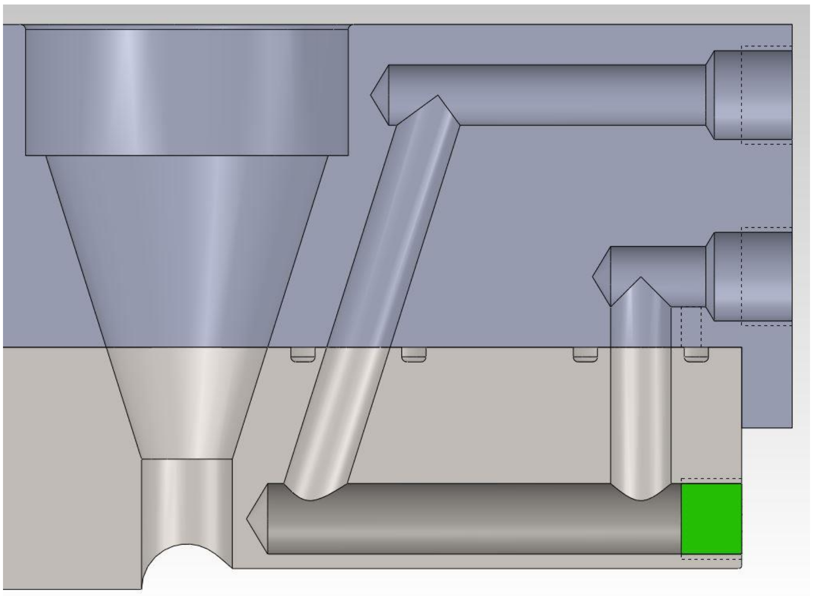


Figure 70: The picture shows the matching cooling holes for Shoulder and Shoulder Holder. The green part on the Shoulder is the M8 conical plug. On the top of the Shoulder the interface for the O-rings can be seen

To determine the needed cooling length of the Shoulder an ANSYS thermal analysis was conducted. As seen in figure 71 the cooling rate starts to stabilise after two seconds. A two second contact between the weld piece and the Shoulder would enable the weld piece to cool down from 500°C to 100°C (see figure 72). The full analysis can be seen in appendix A7. In agreement with ESAB it was decided that two seconds of cooling contact between the Shoulder and the weld piece was sufficient. The length of the cooled part on the Shoulder was therefore set to 50mm, calculating with the maximum welding speed of 1.5m/minute (see equation 13).

$$v = 1.5m/min$$
$$t = 2s$$
$$l = \frac{v * t}{60} = \frac{1.5 * 2}{60} = 0.05m = 50mm \tag{13}$$

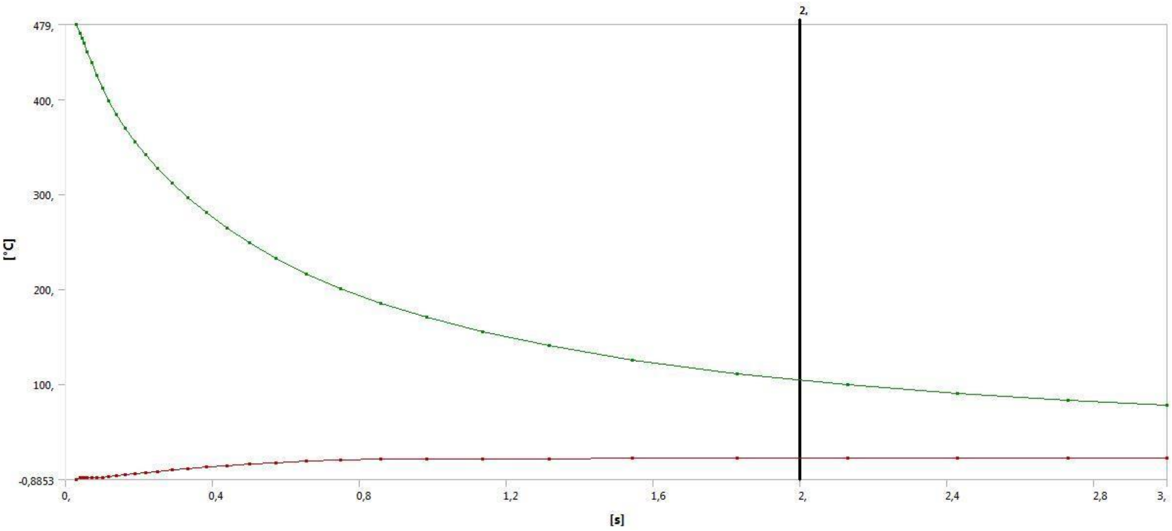


Figure 71: The graph shows the temperature over time for the weld piece during cooling

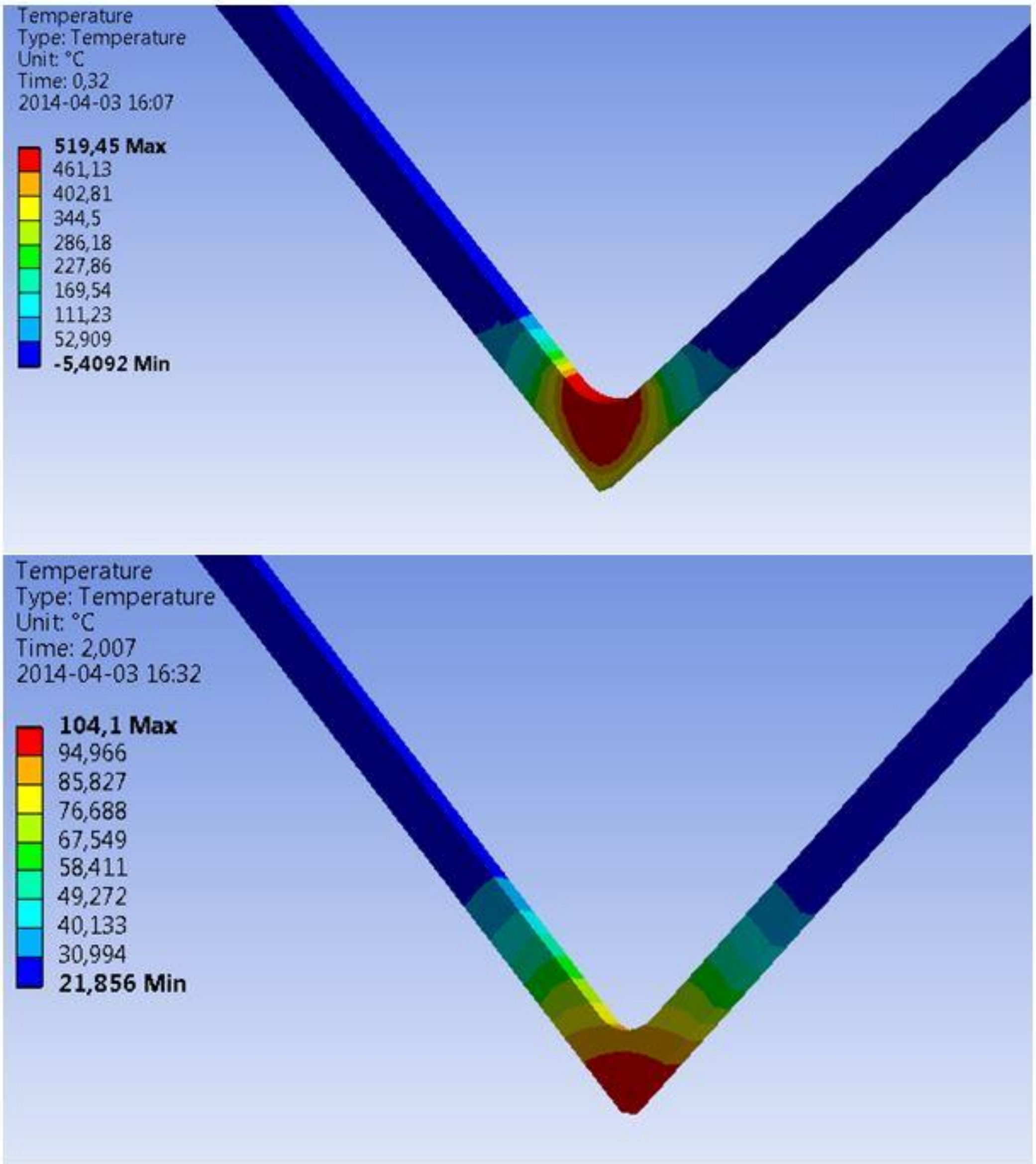
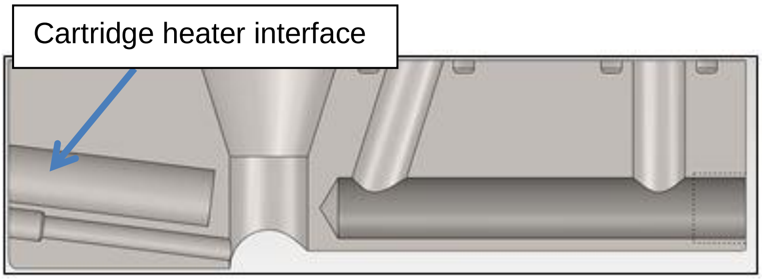


Figure 72: The figure shows the weld piece temperature before (top) and after cooling (bottom). The negative temperature seen in the scale on the top picture is an error in one node and can be ignored. The dark blue temperature is 22^{o}C in both pictures

11.2 Heating

The cooled part of the Shoulder could be made as long as needed since it was not limited by the design of the Arm. This was not the case for the heated part of the Shoulder. It was possible to optimize the design of the Shoulder so that the front could be extended 35mm. This would enable more space for the heating of the Shoulder. The Shoulder was fitted with an angled hole above the Wire Guide hole (see figure 73), working as an interface for the cartridge heater. The cartridge heater with highest power output was found at Backer BHV AB and had a 175W output (Backer BHV AB, 2014).



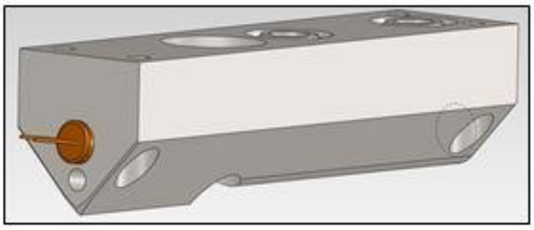


Figure 73: The picture of the left shows the angled hole interface for the catridge heater. The picture to the right is a 3D-view of the Shoulder with the cartridge heater mounted

The heating concept was investigated by assessing the power supply needed to heat the weld piece and the welding wire. The amount of power supplied from the cartridge heater was nowhere near the amount of power needed to heat the weld piece and the welding wire, even without considering the fact that a large amount of heating power would be distributed to the Shoulder and the fixture (see appendix B). The weld zone would however provide a large power supply to the weld piece since it is in direct contact to it as seen in figure 74. While this is hard to assess, it would probably assist in the preheating of the weld piece.

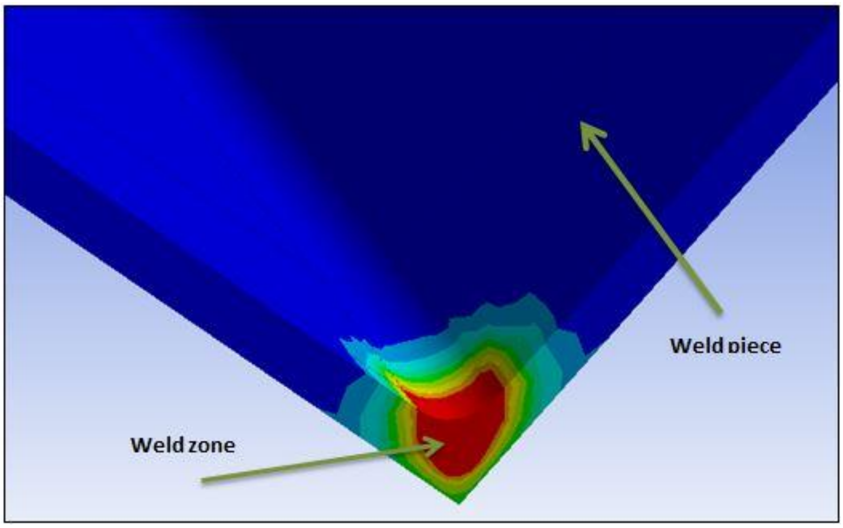


Figure 74: Contact between weld zone and weld piece

For the welding wire, the problem of insufficient power remained. The welding wire was not in direct contact with heated weld zone and would not be heated by it in the same extent as the weld piece. After discussing the heating issue with Backer BHV AB it was decided to use a micro coil around the Wire Guide to transfer more heat to the welding wire (see figure 75). This could solve the heating issue of the welding wire. A micro coil consists of resistance wires with a sheet of nickel. When exposed to electric current, they radiate heat. The micro coil can be used in a straight or coiled form. The micro coil used for the heating concept has a 1.3 X 2.3 cross section and a minimum bending radius of 3mm (ROTFIL, 1999). Using a length that covers 40mm of the Wire Guide would result in a 175W power output of the micro coil.

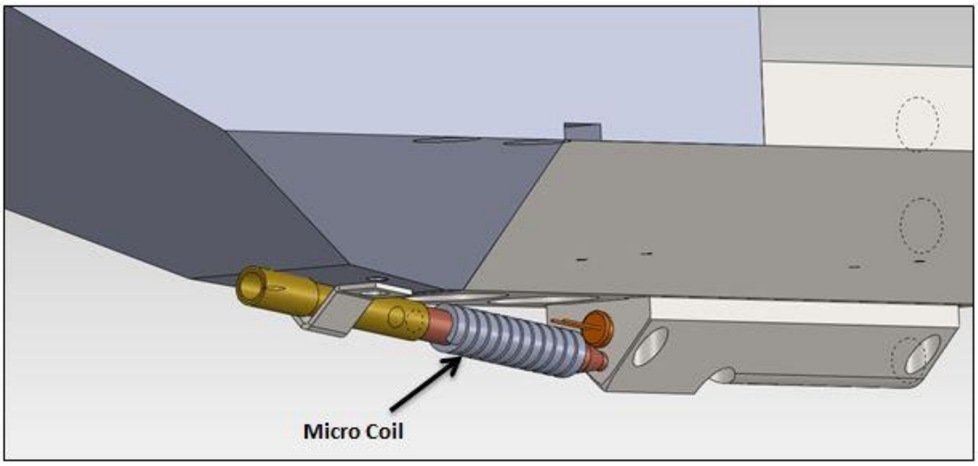


Figure 75: Micro coil placement

It was hard to assess if the supplied power would heat the weld piece to a sufficient temperature. The reason was that the heat zone had a large impact on the temperature of the weld piece immediately in front of the weld. The analysis performed to assess this was regarded to be inadequate to be used as verification. The temperature of the weld piece needs instead to be verified by testing.

The welding wire heating was a simpler heating process since it was heated before the Shoulder and therefore unaffected by the weld zone. The welding wire would of course be affected by the weld zone as it approaches the Probe, but the actual preheating of the welding wire took place before the Shoulder. It was also unclear if the Shoulder would heat or cool the welding wire since the thermal image of the Shoulder was unclear. The supplied power to the welding wire and the resulting temperature were tested in an ANSYS thermal analysis (see appendix A8).

The analysis mainly tested the temperature of the welding wire from the micro coil heat. After passing the micro coil the welding wire would move inside the Wire Guide for approximately 10mm before reaching the Shoulder. This would cause a drop in temperature. The extent of this drop was also tested in ANSYS, the result of this was however proximate since the Shoulder temperature and thus its effect on the welding wire was unclear. The welding wire was preheated to approximately 300^{o}C as it passed the micro coil. This result is considered to be fairly close to the real scenario since the external effects of the weld piece and the weld zone were not present. When reaching the Shoulder the temperature had dropped to 170^{o}C. This result was however regarded as inadequate and needs to be verified by testing.

Both micro coil and cartridge heater are monitored and controlled with a regulator, GEFRAN 1200, from Backer BHV AB. The regulator is mounted on the Arm so that it can be moved with the stroke of the hydraulic cylinder. The mounting interface for the regulator has to be developed in collaboration with Backer BHV AB to get a functional mounting. This has to be done when it is clear that a prototype for the part 2 concept will be manufactured. The regulator enables the temperature to be controlled so that the safety of the heating elements can be ensured. Since the Shoulder had been extended in the welding direction a new Wire Guide had to be constructed. The design was similar to the Wire Guide from the Part 1 concept, but adjusted for the new Shoulder design. The new Wire Guide did not affect the interface between the Wire Guide and the Arm.

12 Future perspective

In this chapter possible improvements of the developed concept and ideas of new development regarding stationary Shoulder FSW are presented.

12.1 Improvements

During the development there was a constant balance in the way the modules were integrated or separated. The main goal was to keep the parts that would be frequently replaced easily replaceable and simple. Making parts easy to replace is a necessity for efficiency when welding different material thicknesses. And by keeping the design simple for the wear parts, the cost can be reduced. However, by integrating modules the number of parts are reduced and by that also the overall complexity. This could provide a more robust concept.

The parts that need to be changed often are the Probe and the Shoulder. Both are exposed for high wear and also need to be replaced when welding different material thicknesses.

The Shoulder is in its current design simple and easy to replace. There is however some restrictions in the Shoulder design that could be improved. The Shoulder has a limit in the Probe diameter that can be used and by that also the material thickness that can be welded. The maximum Probe diameter that can be used in the Shoulder is 16mm. With larger Probe diameters, the Shoulder will not be able to fit the Shoulder Holder. This could be a problem when welding material thicknesses over 20mm with full penetration. To solve this, the height of the Shoulder has to be increased and the Shoulder Holder has to be redesigned to fit the new Shoulder.

Another issue is that the radii length of the Shoulder decreases with an increasing Probe diameter. A shorter radii length might reduce the sealing capability of the Shoulder and the quality of the weld piece fillet. This can however be solved by using the Shoulder design from the part 2 concept.

The Probe is also a part that needs to be replaced when welding different material thicknesses. The concept design does not however allow the Probe to be easily replaced. To change the Probe, the Shoulder Holder needs to be removed. Removing the Shoulder Holder also involves removing the welding wire and the Wire Guide. This makes the process of welding different material thicknesses non-efficient. Easy replacement of the Probe can be solved by increasing the stroke of the Linear Guide by 60mm. By increasing the stroke, the Probe can be replaced without removing the Shoulder Holder. This would however increase the horizontal deflection, as shown in appendix A4. It would also make the construction more expensive.

The Probe is, as mentioned before, exposed to high wear. It is however only the lower part of the Probe, in contact with the weld piece and the Shoulder that is worn. A design opportunity to reduce cost is to reduce the size of the Probe and by doing so only changing worn parts.

This can be done by extending the Probe Holder all the way to the cone of the Shoulder Holder. By doing so, the Probe can be made smaller and therefore cheaper.

Due to the complexity of the part 2 development it is hard to identify any improvement possibilities without testing it. The heating concept can however probably be improved if the design of the part 1 modules were allowed to be changed. This would allow more space to be available and could possibly result in an enhanced heating capability.

12.2 Development possibilities

The stationary Shoulder FSW developed in this thesis has great possibilities for welding fillet welds in aluminium. The layout does however not support welding of planar welds, such as butt or lap welds. This is not possible since the developed Shoulder is dependent on the 90 degree angle of the weld piece to seal the weld. The modular construction of the concept does however support easy replacement of the Shoulder. Developing a Shoulder suitable for planar welds that can be fitted in the developed Shoulder Holder would make the concept an all-round solution, able to perform all types of welds. One obvious advantage with having the opportunity to change to a planar weld Shoulder is that the transition between welding fillet welds and planar welds is simple and efficient. Another advantage with having a stationary Shoulder suitable for planar welds is that the risk of a meltdown is avoided, since the Shoulder slides on a relatively cold weld piece.

One industrial opportunity with the FSW corner weld solution developed in this thesis is manufacturing of aluminium profiles. This would compete with the regular setup of extrusion and TIG welding of aluminium profiles. To make the FSW corner weld solution more competitive, a setup with two Shoulders and Probes can be used. This would enable the possibility to weld two welds at the same time. A tee profile would for example only require one weld process, since both sides would be welded at the same time. Having this approach could possibly also reduce the risk of welding distortion. This setup is not possible with ESAB's current lab machine since two spindle axes are required. When welding with dual spindle axis, the welding heads need to have an offset to avoid clashing, if full penetration is required.

13 Conclusion

The conclusion will discuss the result of the thesis in relation to the objectives, deliverables and preconditions. The conclusion is divided into the part 1 and part 2 development.

13.1 Part 1

The developed part 1 concept was developed meeting all objectives and preconditions. The Probe and Shoulder developed have independent movement and a welding wire is feed directly to the Probe. This was the main objective for the development. The guiding preconditions of the development were to keep the horizontal deflection below 0.2mm, having interfaces suitable for the ESAB lab machine and creating a functional weld with 0.5mm overlap. All objectives and preconditions were met in theory. ESAB was satisfied with developed concept and the prototype is being manufactured at this moment. The deliverable of performing tests on a functional prototype was not met. The reason for this is that the administrative and preparation lead time, before manufacturing could start, was longer than ESAB expected.

13.2 Part 2

The part 2 concept did not have a deliverable of performing tests on a functional prototype. The objective and deliverables included a concept for preheating and cooling the weld piece and to produce manufacturing drawings for the developed parts. These objectives and deliverables were fulfilled and approved by ESAB.

The important preconditions of the part 2 concept were the restrictions in geometry change, the temperature achieved by preheating and the temperature after the cooling. Only the Shoulder, Shoulder Holder and Wire Guide were changed and new manufacturing drawings were developed for these parts, this was in line with the geometrical constraints of the preconditions. The cooling and heating capability of the part 2 concept was tested in ANSYS thermal analysis. The validity of these analyses is hard to confirm due to the high complexity of the welding process. To be able to validate the heating and cooling capability, tests have to be performed with a prototype. It can however be seen from the analysis that the cooling function has good potential of achieving a low temperature and thereby low residual stresses. The preheating according to ANSYS analysis might be insufficient. The power needed to heat the weld piece to a desired temperature could not be transferred to the weld piece from the heating concepts. There is however uncertainties with the impact of the high temperature weld zone. The impact of the hot weld zone on the preheating concept has to be tested with a physical prototype.

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A – ANSYS analysis

This appendix contains all ANSYS analysis used as decision and verification criteria.

A1 – Concept selection 1, Linear Guide

Test of horizontal deflection and wagon reaction forces of Linear Guide concepts. The setup is not used to give a realistic picture of the deflection and forces, but rather a simple comparison of the concepts.

Boundary conditions

Similar boundary conditions were used for the different Linear Guide concepts. The wagons were fixed on their mounting side to be able to investigate the wagon reaction forces. A down force of 10kN, representing the hydraulic pressure, was placed at the flat surface holding the hydraulic cylinder interface. At the welding position a 10kN reaction force from the interface with the welding material and a 7kN friction force were added. The boundary conditions for the different concepts can be seen in figure 1-3.

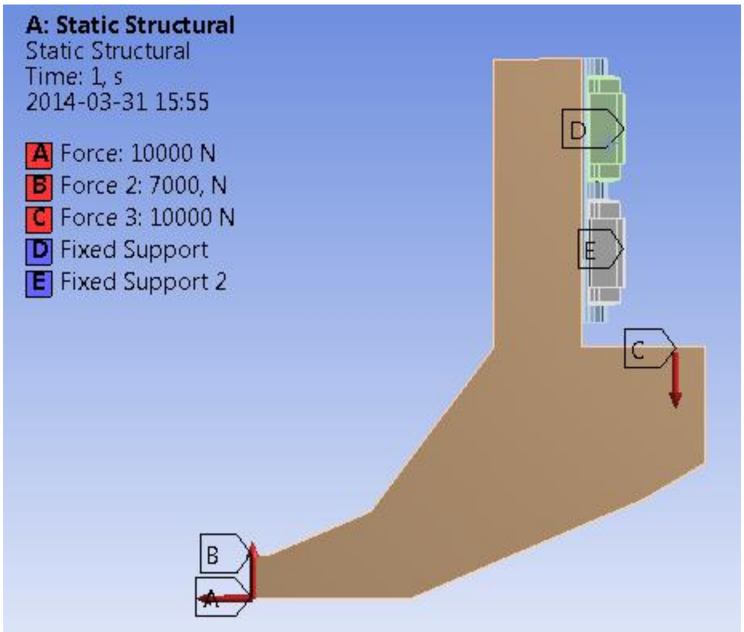

Figure 1: Boundary conditions Outside Wagon

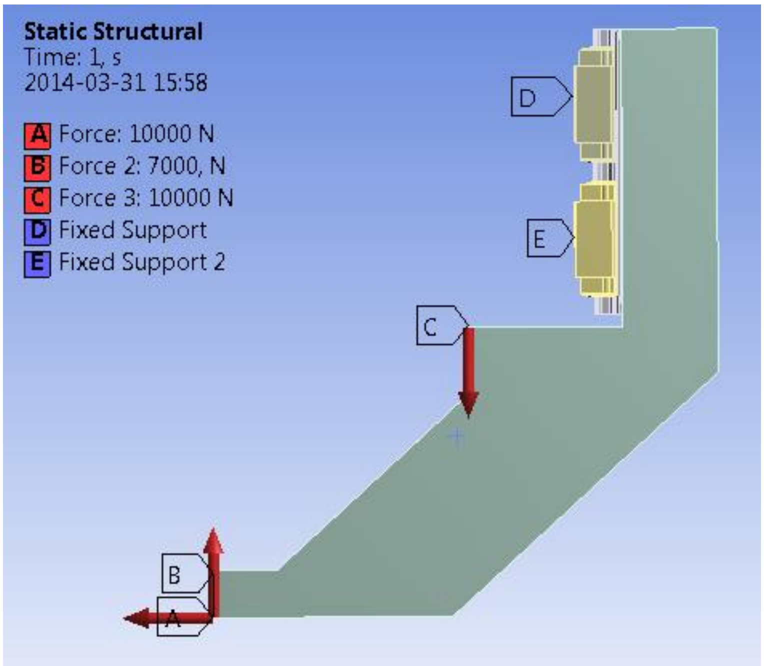

Figure 2: Boundary conditions Outside New

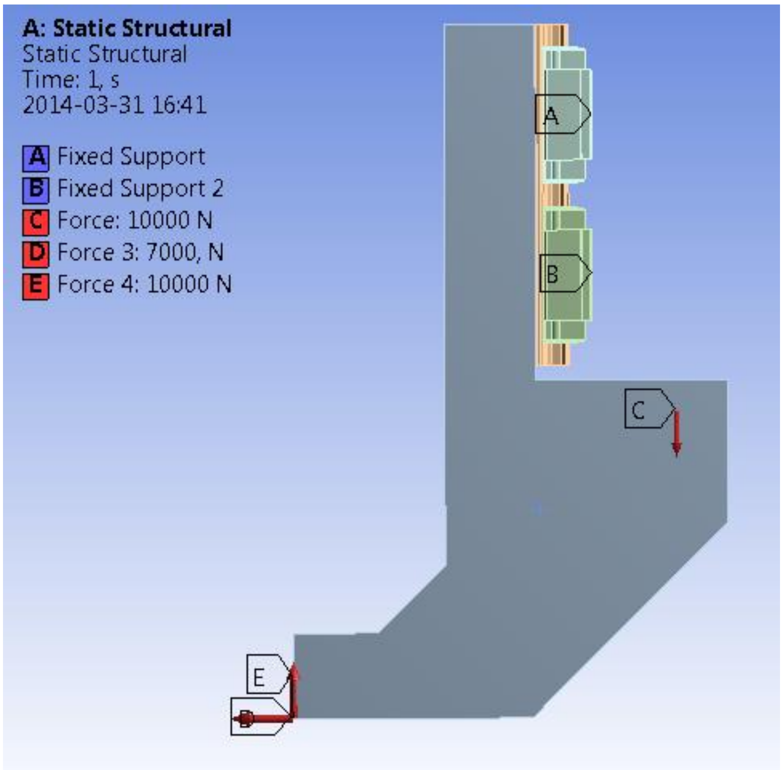

Figure 3: Boundary conditions Enclosed Wagon

Contacts

A bonded contact was used between the rail and the arm. This means that no separation or sliding can occur. The contacts between the wagons and the rail were a “no separation contact”. This means that the components will always be in contact but that they can slide against each other without friction.

Results

The results from the analysis are presented in this chapter. These results were one of the decision criteria for narrowing down the concepts for the Linear Guide. The investigated results were the wagon reaction force and the horizontal deflection. The horizontal deflection of the three concepts can be seen in figures 4-6. The wagon reaction forces were investigated with a force Probe on the fixed wagons. A table of all the concepts wagon reaction forces and their horizontal deflection can be seen in table 1.

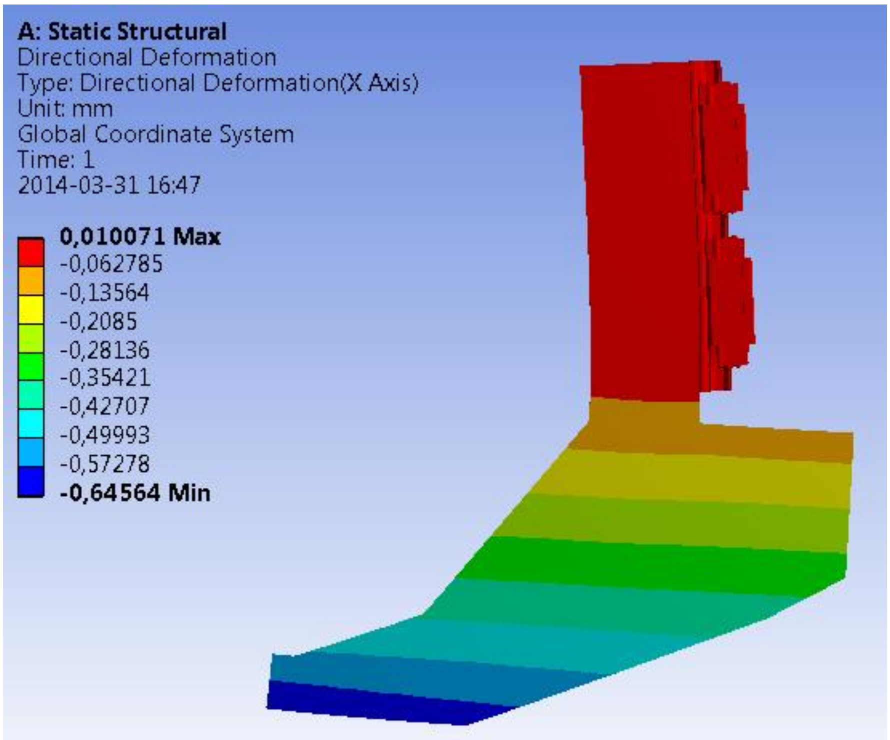

Figure 4: Horizontal deflection Outside Wagon

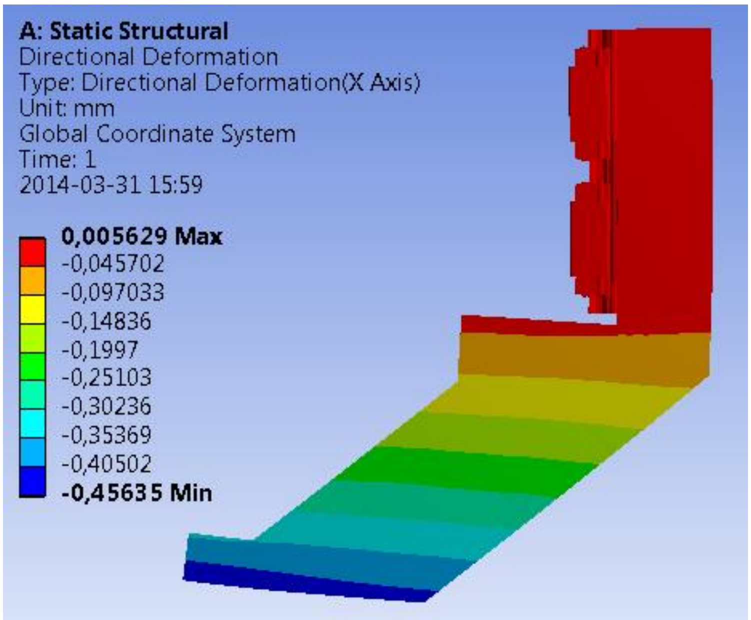

Figure 5: Horizontal deflection Outside New

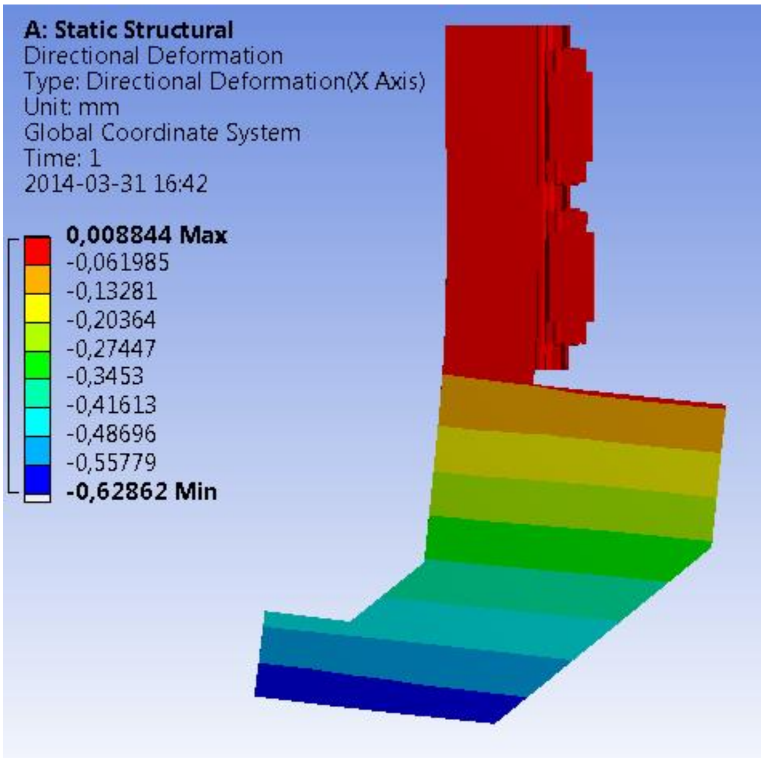

Figure 6: Horizontal deflection Enclosed Wagon

Table 1: Wagon reaction forces and horizontal deflection for Linear Guide concepts

Concept	Force reaction top wagon [kN]	Force reaction bottom wagon [kN]	Max deflection [mm]
Outside Wagon	38.5	45.5	0.66
Outside New	27.8	34.8	0.46
Enclosed Wagon	28.3	35.3	0.62

A2 – Concept selection 2, Linear Guide

Test of horizontal deflection and the wagon reaction forces for the Enclosed Wagon and Outside New Linear Guide concepts. The test was mainly set up to get a comparison of the two concepts. It also served as a first look at how large the horizontal deflection and the wagon reaction forces could be.

Boundary conditions

Similar boundary conditions were used for the different Linear Guide concepts. The wagons were fixed on their mounting side to be able to investigate the wagon reaction forces. A down force of 10kN, representing the hydraulic pressure, was placed at the flat surface holding the hydraulic cylinder interface. At the welding position a frictionless support was added to the Shoulder to simulate the reaction force from the weld piece. A 7kN friction force was also added at the interface between the Shoulder and the weld piece. The boundary conditions for the two concepts can be seen in figure 7 and figure 8.

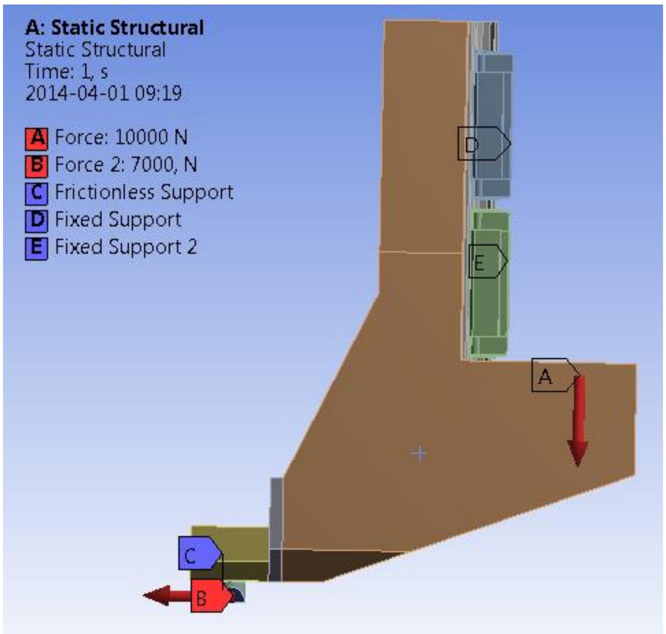

Figure 7: Boundary conditions Enclosed Wagon

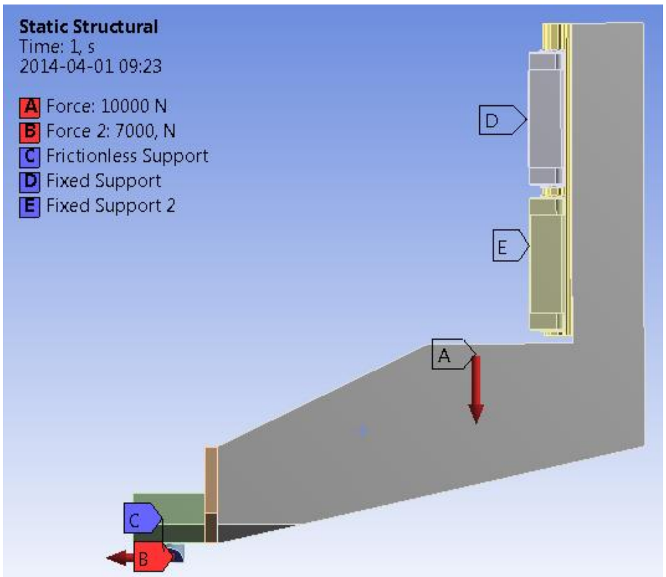

Figure 8: Boundary conditions Outside New

Contacts

All contacts between components that were welded or screwed together were regarded as bonded. This means that no separation or sliding can occur**.** The contacts between the wagons and the rail were a “no separation contact”. This means that the components will always be in contact but that they can slide against each other without friction.

Results

The results from the simulations are presented in this chapter. These results were one of the decision criteria for choosing the concept for the Linear Guide. The investigated results were the wagon reaction force and the horizontal deflection. The horizontal deflection of the two concepts can be seen in figure 9 and figure 10. The wagon reaction forces were investigated with a force Probe on the fixed wagons. The two concepts wagon reaction forces and their horizontal deflection can be seen in table 2.

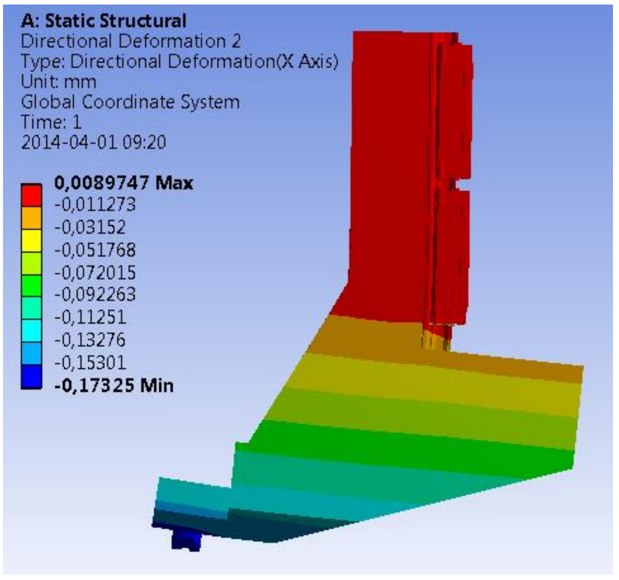

Figure 9: Horizontal deflection of the Enclosed Wagon concept

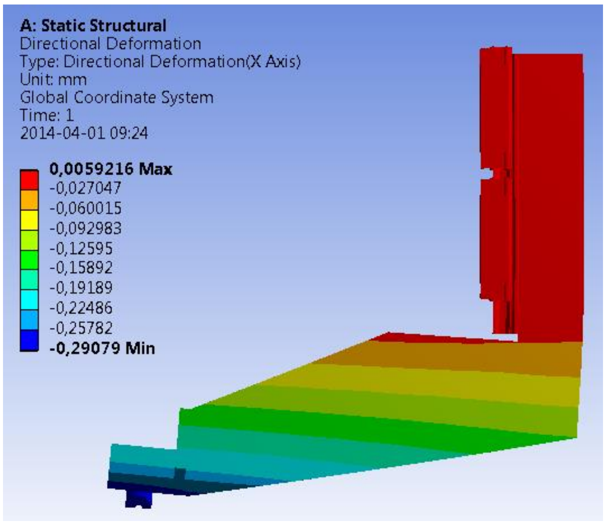

Figure 10: Horizontal deflection of the Outside New concept

Table 2: Wagon reaction forces and horizontal deflection for Linear Guide concepts

Concept	Force reaction top wagon [kN]	Force reaction bottom wagon [kN]	Max deflection [mm]
Enclosed Wagon	18.9	25.9	0.17
Outside New	18.5	25.5	0.29

A3 – Probe and bearing concept selection

The analysis was made to discover stress and horizontal deflection differences in different sizes of the Probe. The analysis was also used for investigating the impact of using a bearing between the Shoulder Holder and the Probe.

Boundary conditions

The boundary conditions used in the analysis can be seen in figure 11.

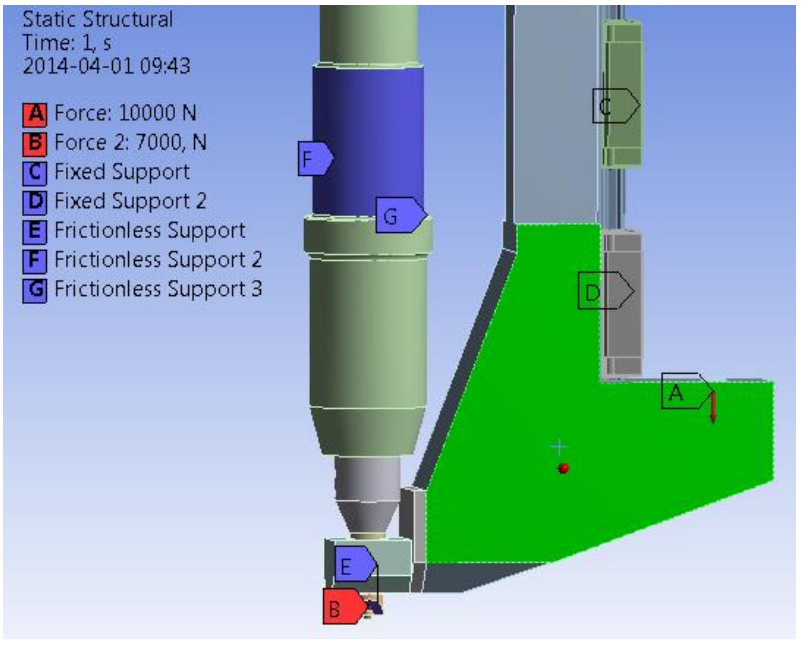

Figure 11: Boundary conditions

A. Down force from the hydraulic cylinder
B. Friction force on the Shoulder
C. Fixed support on the top wagon
D. Fixed support on the bottom wagon
E. Vertical support on the Shoulder from the weld piece
F. Frictionless support from the radial lab machine bearing
G. Frictionless support from the axial lab machine bearing

Contacts

All contacts between components that were welded or screwed together were regarded as bonded. This means that no separation or sliding can occur. Components that have a sliding contact were given the “no separation” contact condition. This means that the components will always be in contact but that they can slide against each other without friction.

Results

The results from the analysis are presented in this chapter. The results were decision criteria for selecting a Probe and Shoulder Holder concept. The investigated results were the horizontal deflection and the von Mises stress of the Probe and the bearing. In figure 12-14, the horizontal deflection of the Probe concepts are shown. In figure 15, the horizontal deflection for the small Probe concept without a bearing is showed. Table 3 shows the stress of the Probe concepts and the bearing, it also shows the stress of the Probe when used without a bearing and all horizontal deflections.

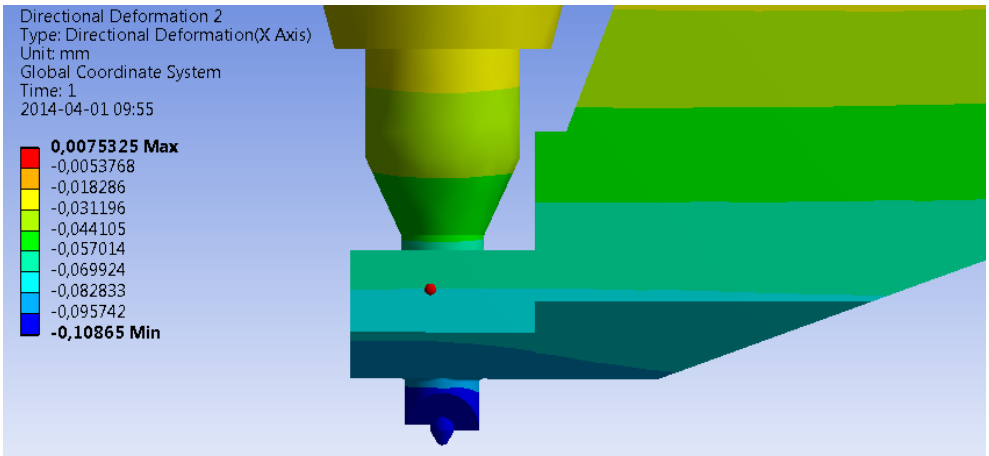

Figure 12: Probe small horizontal deflection

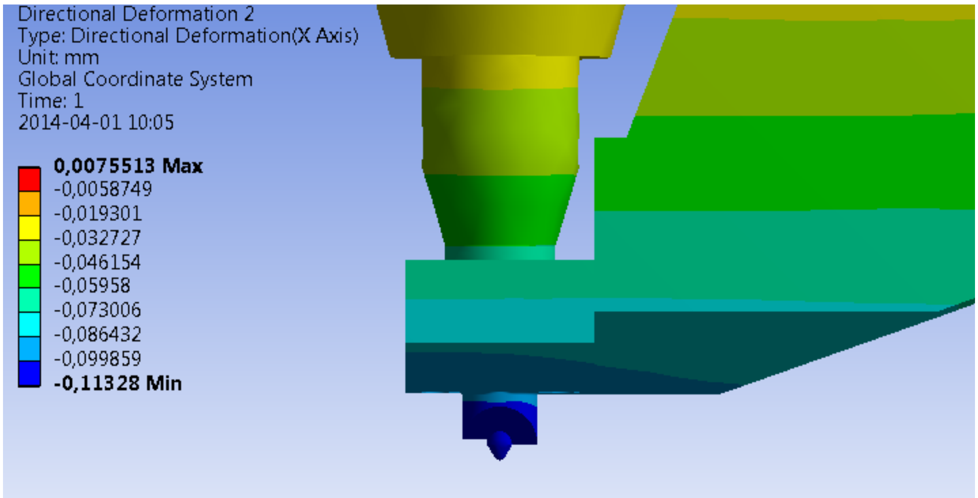

Figure 13: Probe medium horizontal deflection

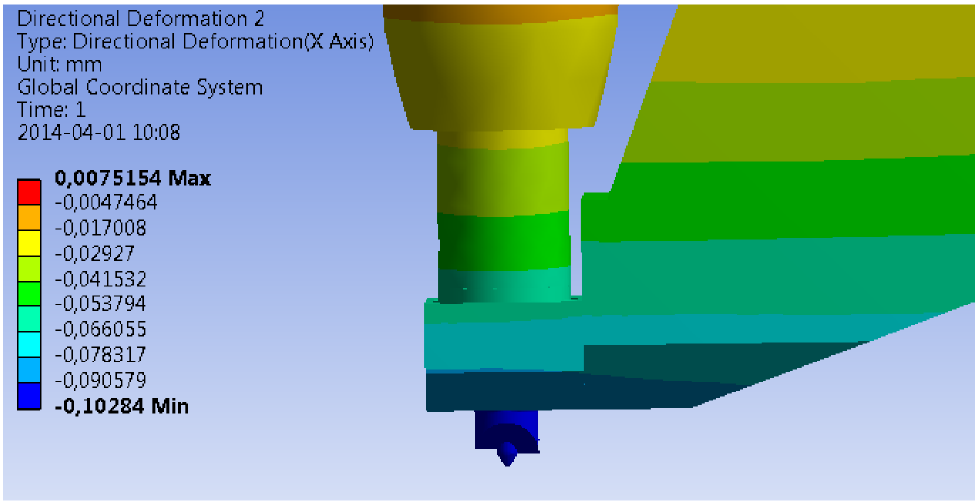

Figure 14: Probe large horizontal deflection

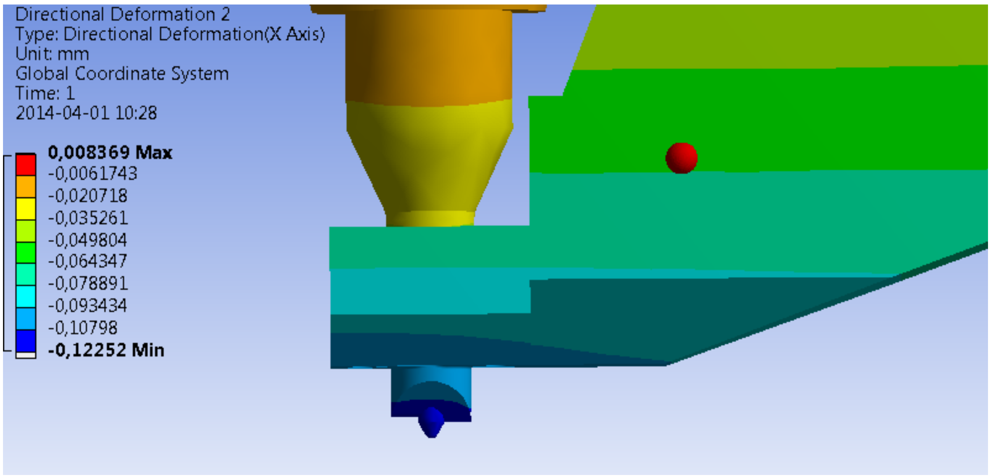

Figure 15: Probe small without bearing horizontal deflection

Table 3: Stress and horizontal deflection of investigated concepts

Concept	Deflection[mm]	Stress von Mises [MPa]
Small Probe	0.11	18.5
Medium Probe	0.11	28.3
Large Probe	0.10	25.5
Bearing stress	-	14.7
Small Probe without bearing	0.13	84.1

A4 – Final concept simulation, part 1

The final concept simulations were made to give a view of how the components were affected by the forces present at a welding operation. The layout was made as realistic as possible to be able to make the right design decisions. It was also used to verify components when it comes to stress and horizontal deflection.

Boundary conditions

Two boundary conditions were used through the analysis. In the first, the most realistic setup was used with the mounting plate included. In the latter, the mounting plate was removed to be able to investigate the wagon reaction forces. The boundary conditions for the first analysis can be seen in figure 16.

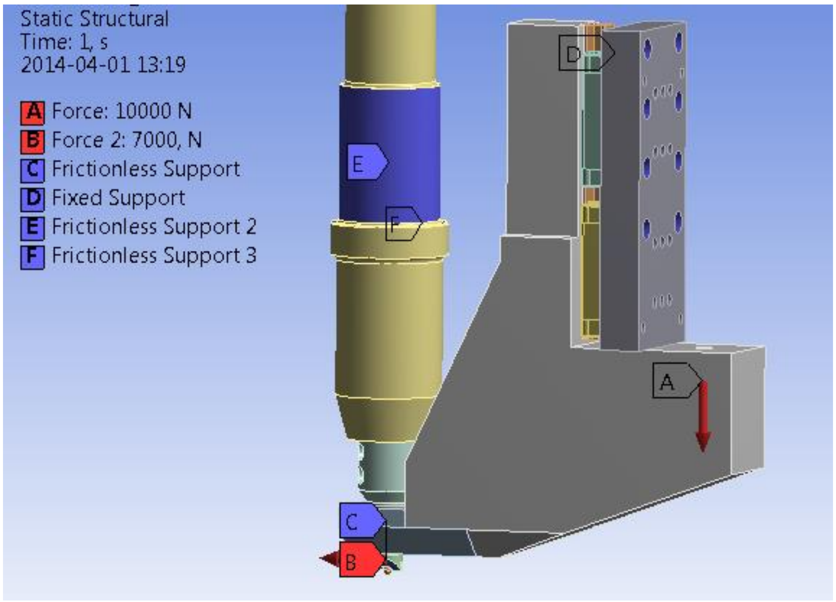

Figure 16: Boundary conditions with mounting plate

A. Down force from the hydraulic cylinder
B. Friction force on the Shoulder
C. Vertical support on the Shoulder from the weld piece
D. Fixed support from the mounting holes on the mounting plate
E. Frictionless support from the radial lab machine bearing
F. Frictionless support from the axial lab machine bearing

In figure 17 the boundary conditions for the simplified analysis, with the mounting plate removed, is shown. Fixed supports were added on the wagons to be able to investigate the reaction force from the fixed support. This force is probably higher than in the real case since the mounting plates natural suspension is removed, thus giving a worst case scenario. Other than that, the boundary conditions are the same as in the figure 16 analysis.

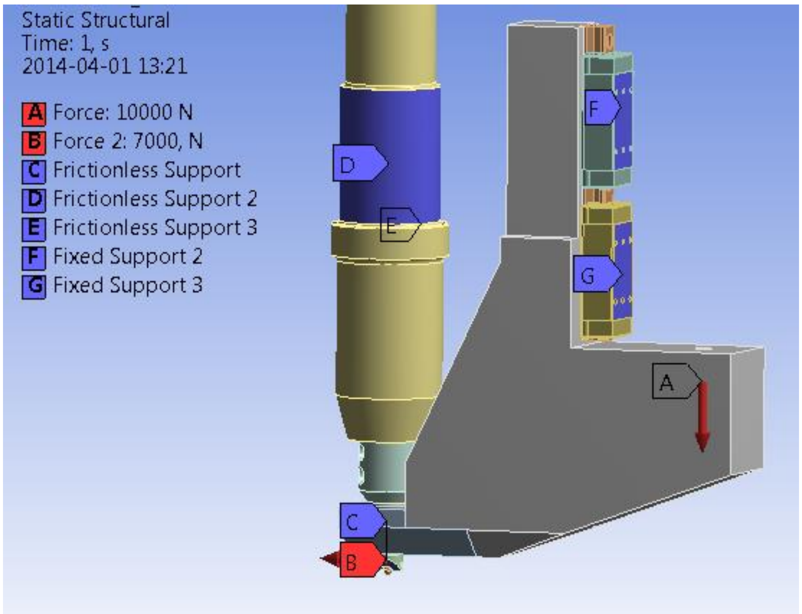

Figure 17: Boundary conditions without mounting plate

Contacts

All contacts between components that were welded or screwed together were regarded as bonded. This means that no separation or sliding can occur. Components that have a sliding contact were given the “no separation” contact condition. This means that the components will always be in contact but that they can slide against each other without friction.

Results - Deflection from short and long rail

A test was performed to investigate the impact on deflection of a longer rail compared to shorter one. This was tested with the boundary conditions seen in figure 16. The horizontal deflection can be seen in figure 18, figure 19 and table 4.

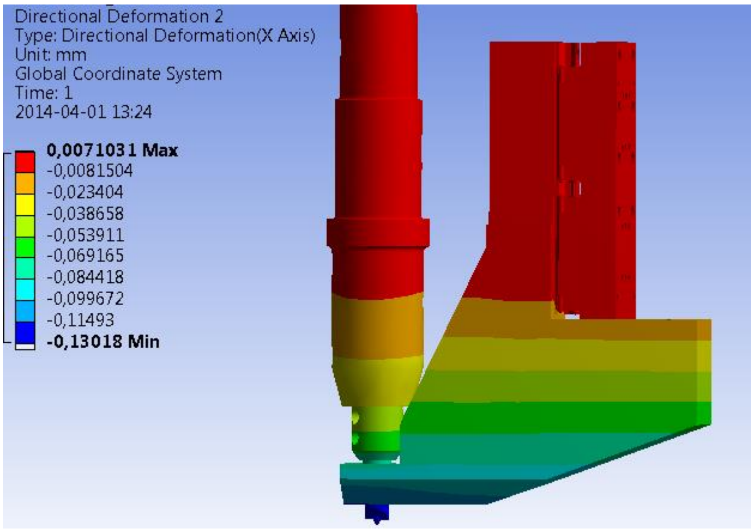

Figure 18: Horizontal deflection, short rail

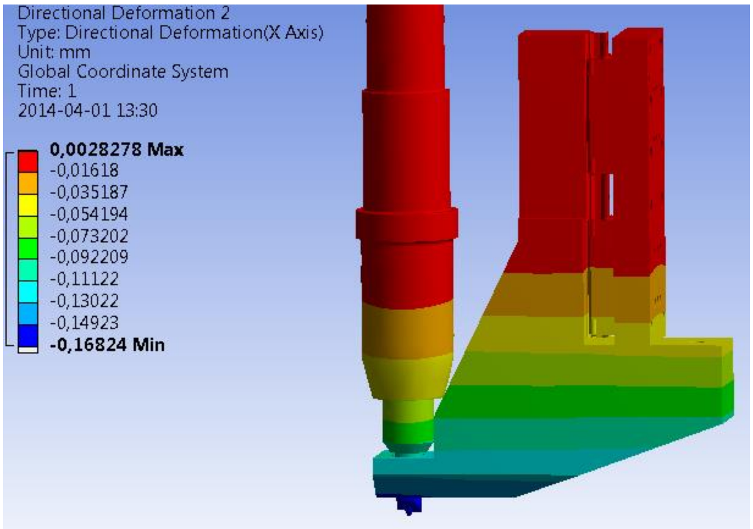

Figure 19: horizontal deflection, long rail

Table 4: Horizontal deflection of short and long rail

Concept	Max Deflection[mm]
Short rail (266mm)	0.13
Long rail (300mm)	0.17

Results – Probe and bearing stresses

The resulting von Mises stresses on the Probe and bearing were investigated for the short rail system. This was tested with the boundary conditions seen in figure 16. The stresses were investigated through a stress Probe on the selected components and the maximum stresses were noted together with their stress limit in table 5.

Table 5: Von Mises stress and stress limit for Probe and bearing

Component	Max von Mises stress [MPa]	Stress limit [MPa]
Probe	36.8	1620 (yield strength)
Bearing	18.4	140 (max dynamic stress)

Results – Wagon reaction forces

The reaction forces on the wagons were investigated to verify that the chosen Aluflex wagons could be used. The reaction forces were compared to the given force limits of the wagons from the manufacturer as seen in table 6. Figure 20 and figure 21 shows the direction of the wagon reaction forces.

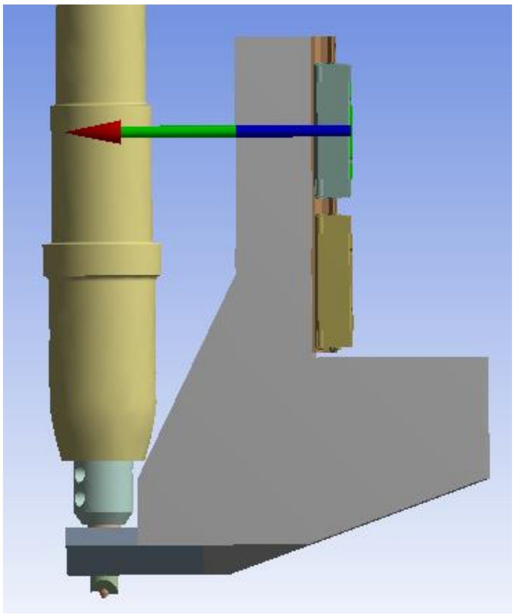

Figure 20: Reaction force, top wagon

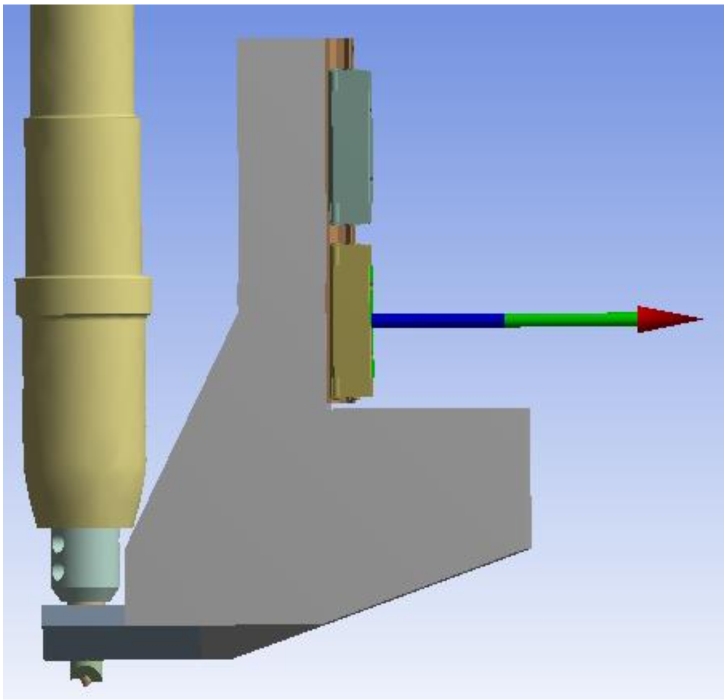

Figure 21: Reaction force, bottom wagon

Table 6: Wagon reaction forces and force limits

Wagon	Calculated Force [kN]	Force limit [kN]
Top	12.2 (pushing)	34.4 (pushing)
Bottom	11.0 (pulling)	28.1 (pulling)

A5 – Concept selection, cooling

A thermal analysis was performed to evaluate the Cooling Pipe and Cooling Plug concepts. The analysis was used to get a comparison between the concepts and does not represent the real welding operation.

Boundary conditions

The whole Shoulder had a start temperature of 300°C. The welding area were the Probe would be situated had a constant temperature of 400°C and a convection of 22°C with a heat transfer coefficient of 1.7e-2 W/mm^2 that was placed in the cooling tube. The heat transfer coefficient was calculated using equation 12 in section 10.1. The initial temperature simulated that the Shoulder had been preheated from the welding. After that, the Shoulder is cooled by the tube and at the same time heated from the back as it would be in the real situation. The analysis was run for 10 seconds, the time were used to see how the cooling evolved over time. The set up was not realistic, but useful for comparing the cooling capabilities of the tested concepts. The boundary conditions for the two concepts can be seen in figure 22 and figure 23.

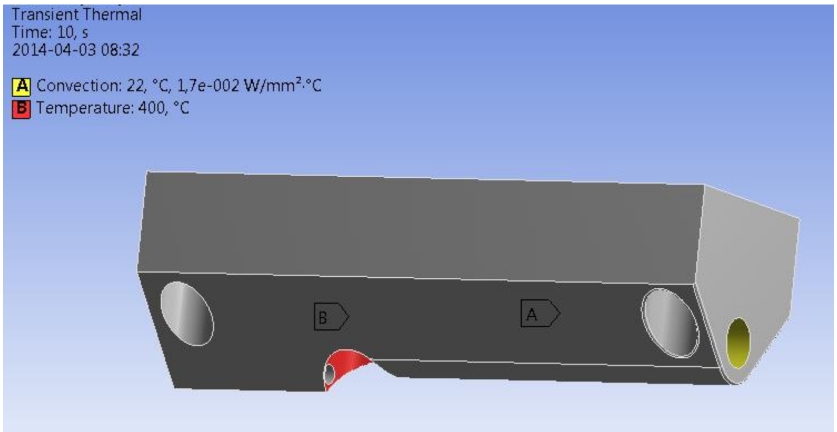

Figure 22: Boundary conditions for the Cooling Pipe concept

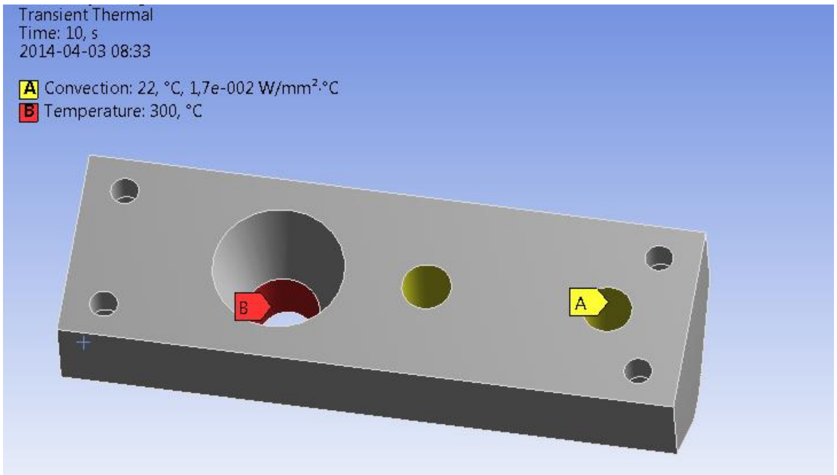

Figure 23: Boundary conditions for the Cooling Plug concept

Results

The interesting aspect of the results was the temperature at the bottom of the Shoulder where the contact with the weld piece would be. It was also interesting how close to the 400°C welding area the minimum temperature would reach. A low temperature close to the welding area would ensure faster immediate cooling of the weld piece. The Shoulder temperature after a 10 second analysis can be seen in figure 24, figure 25 and table 7.

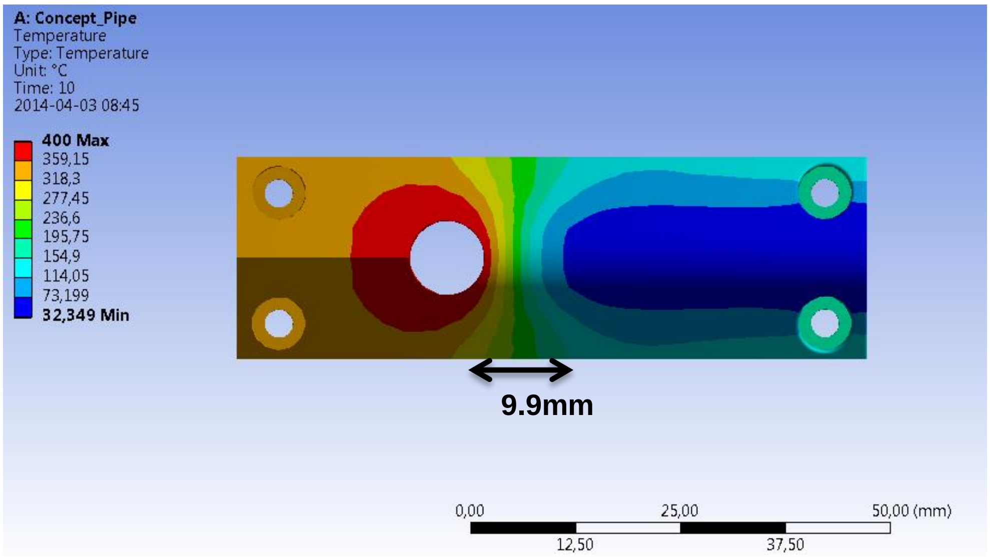

Figure 24: Temperature after 10 seconds for the Cooling Pipe concept

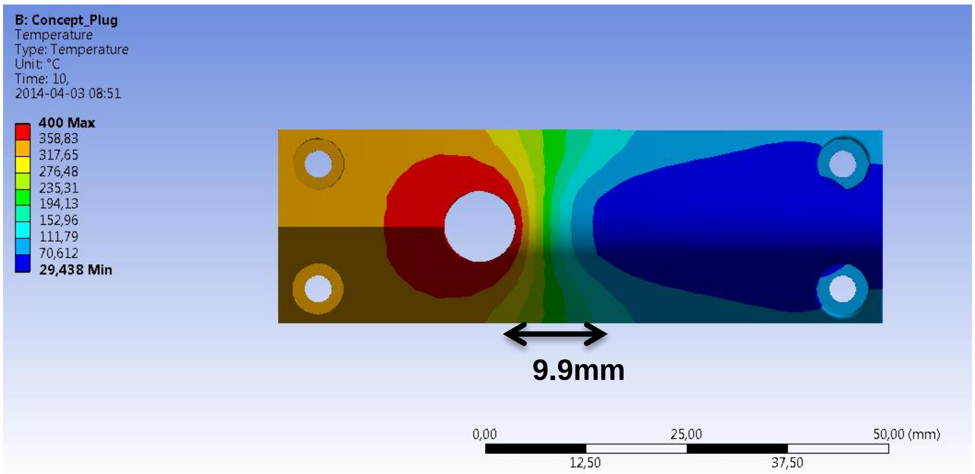

Figure 25: Temperature after 10 seconds for the Cooling Plug concept

Table 7: Minimum temperature and distance between heat source and minimum temperature area

Concept	Minimum temperature [°C]	Minimum temperature distance from heat source [mm]
Cooling Pipe	32.3	9.9
Cooling Plug	29.4	9.9

A6 – Concept selection, insulation

A thermal analysis was performed to evaluate the Insulation plate concept against the No Insulation concept. The analysis was used to get a comparison between the concepts and does not represent the real welding operation.

Boundary conditions

The boundary conditions were configured to get a view of how well the hot side and cold side of the Shoulder were insulated. Both insulation concepts had the chosen heating and cooling concepts incorporated. In the analysis the front of the Shoulder had the same layout for both concepts, with a heat flux representing the heating from the cartridge heater and a constant temperature at the welding area. The back of the Shoulder were configured for the respective concept. The Insulation Plate concept had a shortened water tube path and a stainless steel insulation plate. The No Insulation concept had the regular water tube path. The analysis was run for 10 seconds so that the temperature had time to stabilize. The geometry and the boundary conditions for the two concepts can be seen in figure 26 and figure 27.

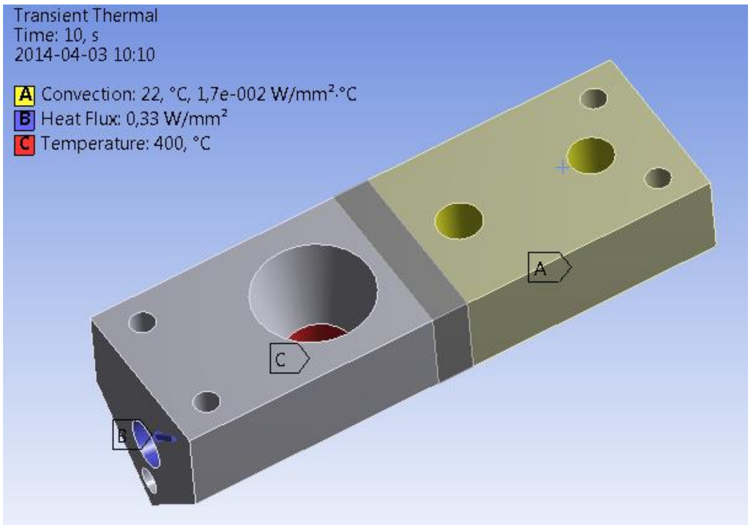

Figure 26: Boundary conditions for Insulation Plate concept

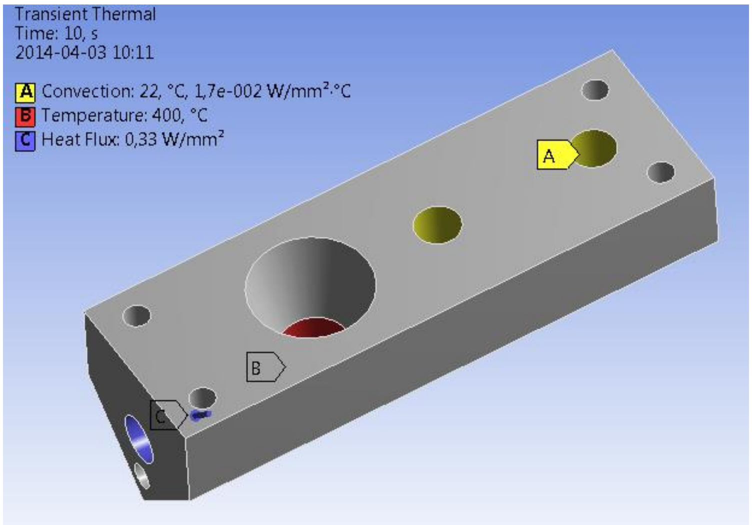

Figure 27: Boundary conditions for No Insulation concept

Results

The investigated result was the temperature at the interface between the cold side and the hot side at the radii of the Shoulder. More specifically, at what distance from the welding heat zone the temperature had decreased to water temperature. The resulting Shoulder temperature for the two concepts can be seen in figure 28, figure 29 and table 8.

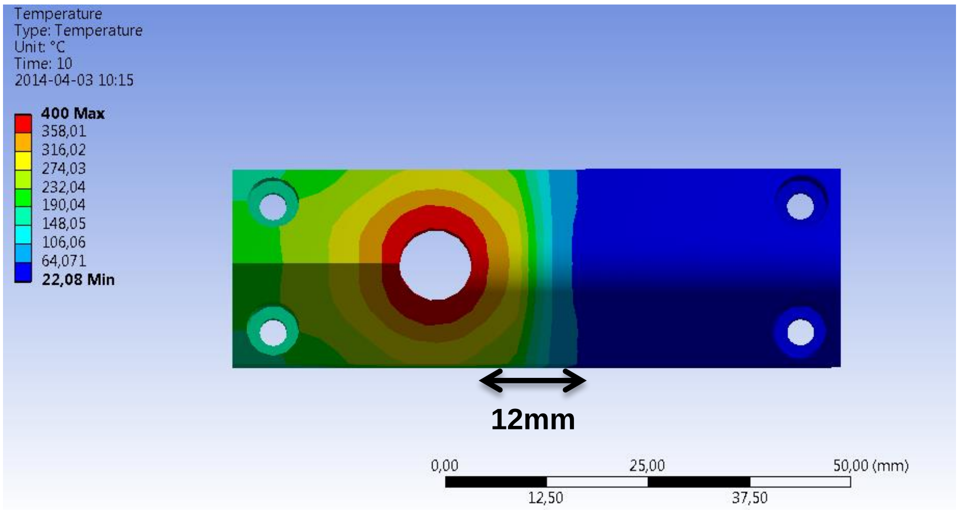

Figure 28: Temperature after 10 seconds for the Insulation Plate concept

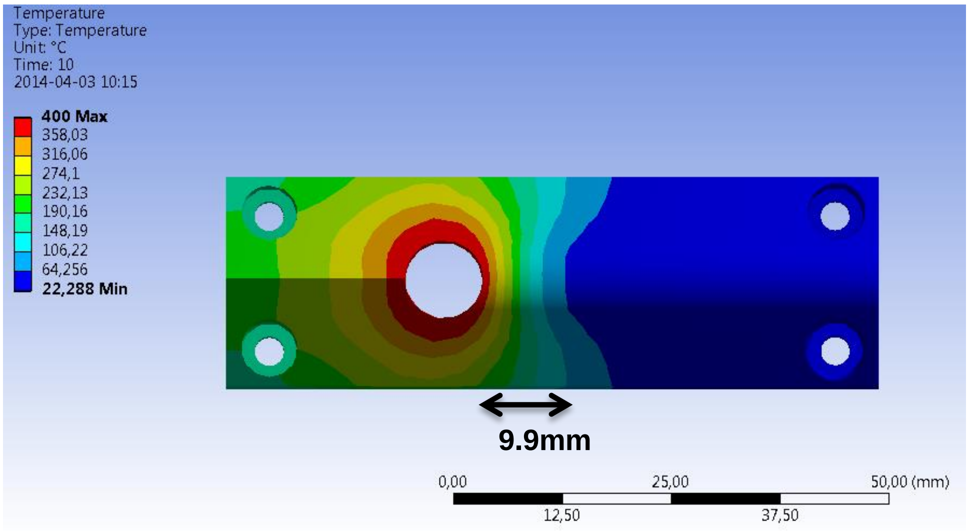

Figure 29: Temperature after 10 seconds for the No Insulation concept

Table 8: Distance between heat source and minimum temperature area for Insulation Plate and No Insulation concepts

Concept	Distance between heat source and minimum temperature [mm]
Insulation Plate	12
No Insulation	9.9

A7 – Final concept analysis, cooling

A detailed thermal analysis was performed to determine the cooling capabilities of the final cooling concept. This was made to be able to determine the needed cooling length of the Shoulder to cool down the weld piece to sufficient low temperature.

Geometry

The analysis was performed with a transient thermal analysis without any dynamics. Since the problem is in fact dynamic, with a horizontally moving Shoulder, this had to be solved through other analysis setups. Figure 30 shows the geometry used for the analysis.

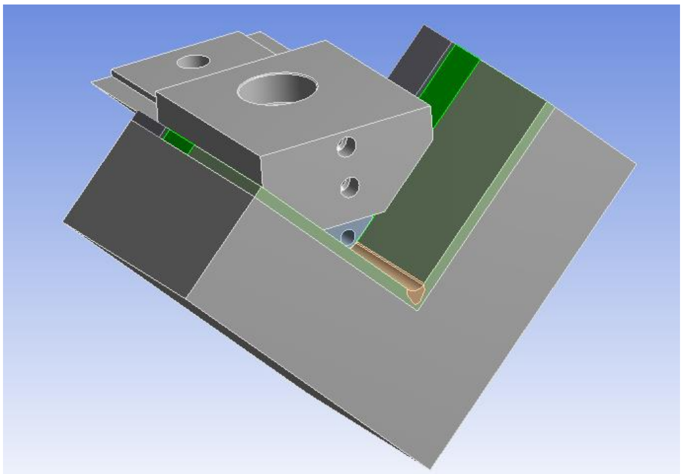

Figure 30: Geometry for the final cooling concept analysis

The weld piece thermal image was solved by dividing the weld piece in into small parts (see figure 31). The welding interface was secluded to identify the thermal image of the weld piece immediately after the welding. The weld piece was also split into horizontal pieces. Three pieces that are in contact with the Shoulder and exposed for the cooling at a time in accordance with the travel rate of the Shoulder and the length of the Shoulder. The middle piece of these was secluded to be able to get a mean temperature, not affected by the temperature conditions at the edges (see figure 32). The front of the weld piece, not in contact with the Shoulder serves as a coolant, allowing heat transfer from the weld piece in contact with the Shoulder. A solid was added below the weld piece to simulate the fixture holding the weld pieces. This was needed to get a proper heat transfer from the bottom of the weld piece. The weld piece was simulated as aluminium and the other parts as steel.

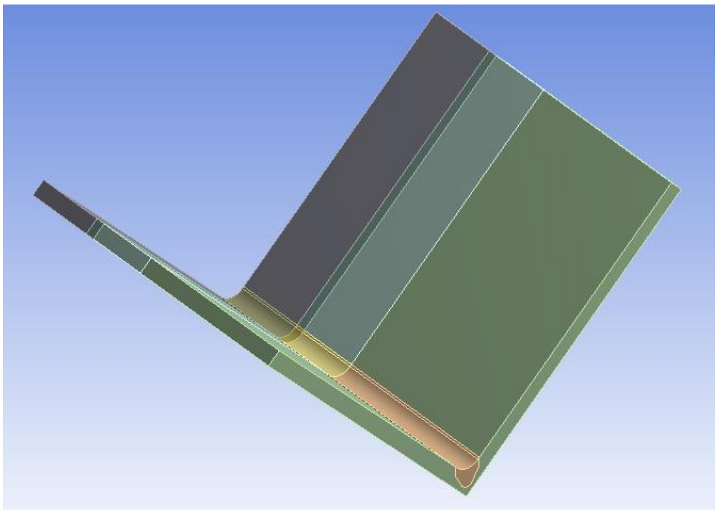

Figure 31: Weld piece segments

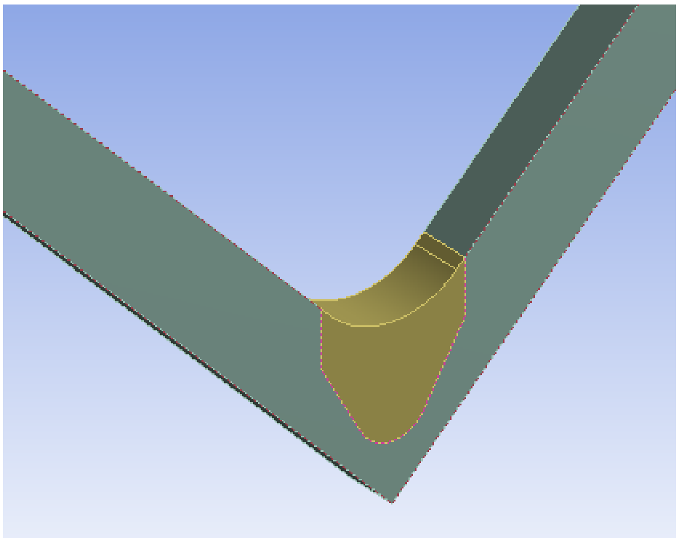

Figure 32: Middle weld piece, with secluded weld zone

Boundary conditions and analysis

The analysis was performed in three steps to be able to get the proper thermal image of the geometry before the actual cooling analysis. The subsequent analysis was given the boundary conditions from the thermal image of the previous analysis. The length of the Shoulder and the weld piece served no real purpose in this simulation. Instead, the cooling length was simulated by the analysis time. The analysis time together with welding speed gave the analysed cooling length.

In the first step a temperature of 500°C was placed on the welding interface of the weld piece (see figure 33). The analysis was run for 0.32 seconds, which is the time the area of the weld piece is in contact with the Probe of 8mm diameter with a welding speed of 1.5 m/min.

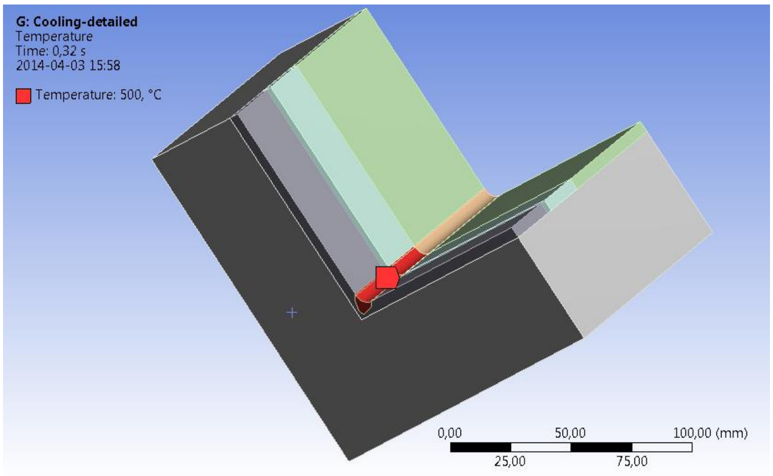

Figure 33: Boundary conditions for the first step in the analysis

This analysis provided the thermal image of the weld piece immediately after the welding operation as seen in figure 34.

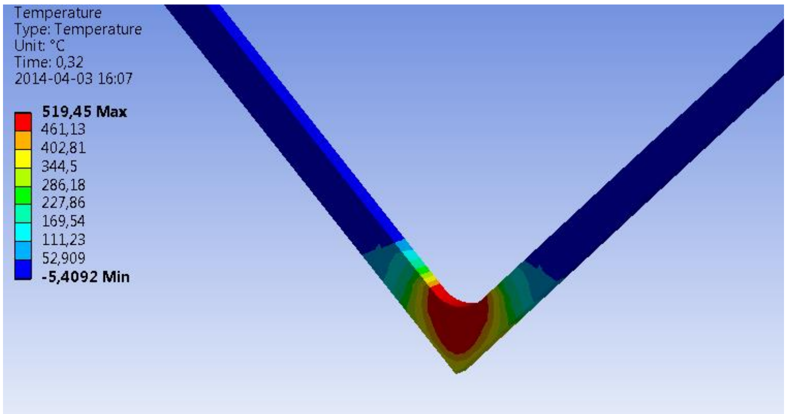

Figure 34: Thermal image of a section of the weld piece after first analysis step

Since the weld piece was in contact with the Shoulder during the analysis the Shoulder was also heated up. This is not realistic since in the real case the heated weld piece would move from the weld zone to a cooled Shoulder. A second analysis was therefore performed to get the proper thermal image of the Shoulder as well (see figure 35).

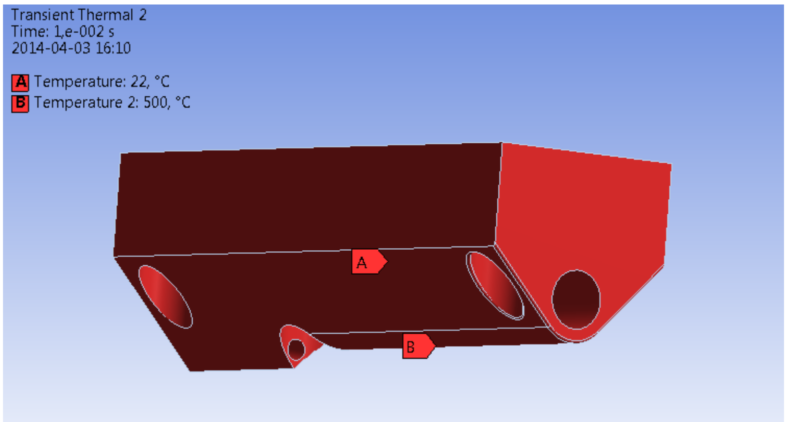

Figure 35: Boundary conditions for the second step in the analysis

This analysis provided the proper temperature for both Shoulder and the weld piece (see figure 36). The Shoulder was given a temperature of 22°C to simulate the weld piece being exposed to a cooled Shoulder. The radius of the Shoulder was given the welding temperature to avoid affecting the weld piece of the cooled Shoulder. This setup gave a Shoulder at room temperature with the area in contact with the weld piece at welding temperature. The weld piece still held the temperature image from the previous analysis. Since this analysis only served to set the boundary conditions for the subsequent analysis it was only run for 0.01 seconds.

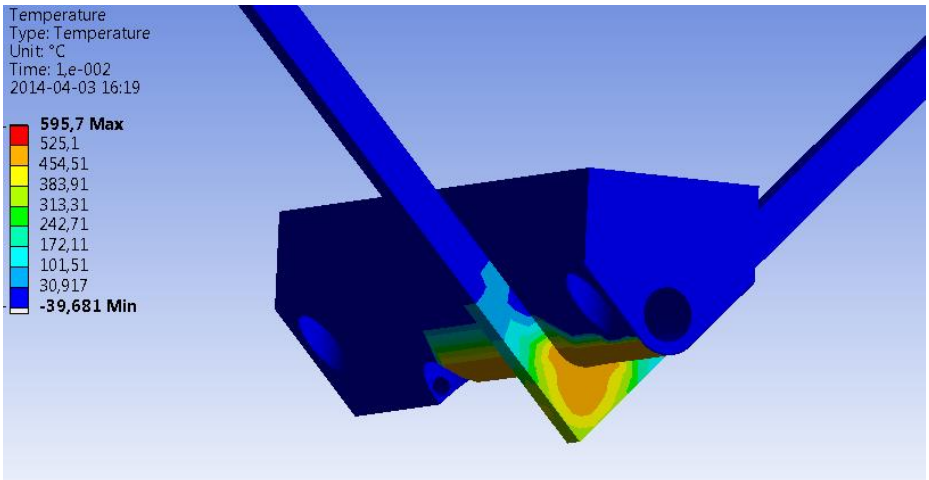

Figure 36: Thermal image of the weld piece and Shoulder after the second analysis

From the two first analyses the temperature boundary conditions were set. The third analysis served as the test of the cooling capability of the Shoulder to identify the proper cooling length of the Shoulder.
Convection was added to the Shoulder and the Shoulder Holder to simulate the water flow as seen in figure 37. The calculated convection coefficient adjusted for the water flow rate and properties was calculated to 1.7e-2 W/mm^2 from equation 12 in section 10.1.

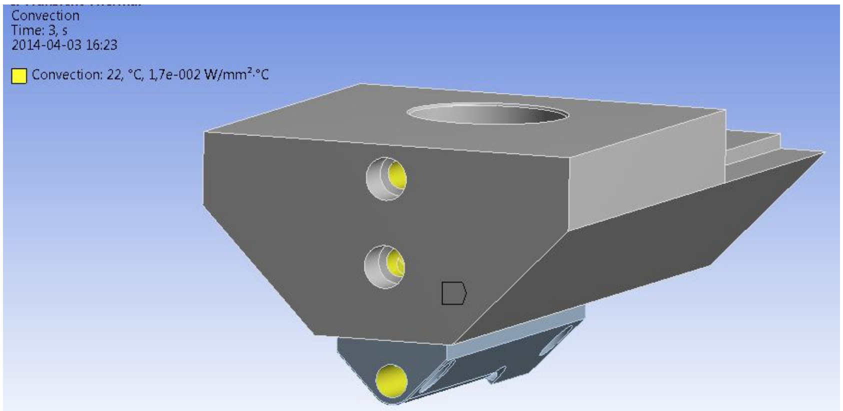

Figure 37: Convection boundary condition for third analysis step

The temperature over time was investigated for the cross section of the weld piece over time to identify the optimum cooling time (see figure 38). From the optimum cooling time the optimum cooling length could be calculated with equation 13 in section 11.1.

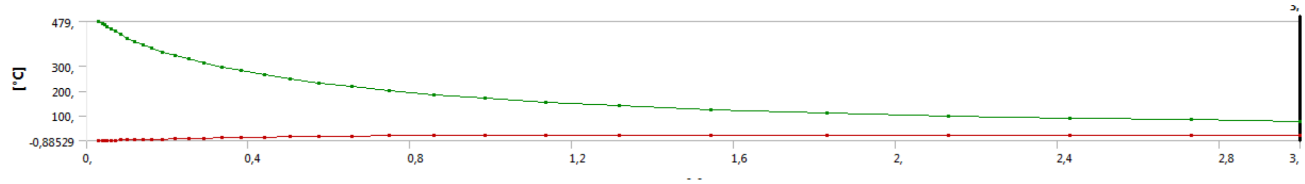

Figure 38: Weld piece temperature over time for third analysis step

The temperature graph showed that the weld piece had been cooled to an acceptable level after ca 2 seconds. This was concluded in collaboration with ESAB. It could also be seen that the temperature had begun to stabilize at that time, which meant that a longer cooling time would not give a significant change in cooling. The temperature image of the weld piece cross section can be seen in figure 39. The cooling time of 2 seconds led to a cooling length of 55mm according to equation 13 in section 11.1.

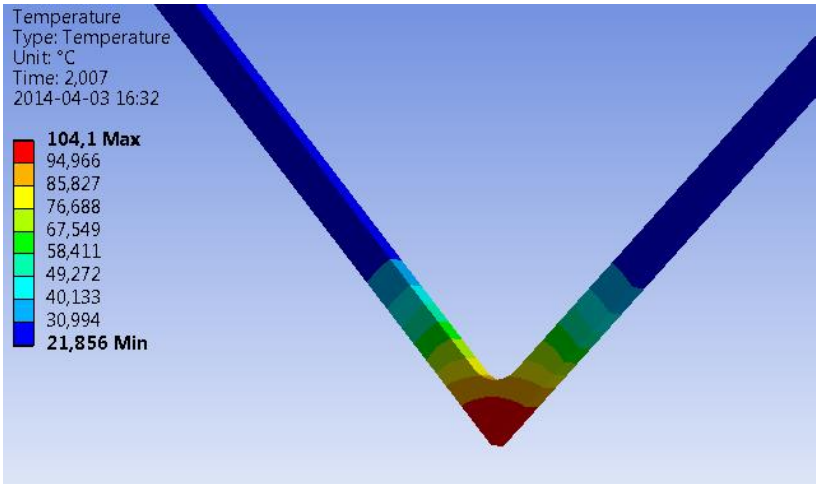

Figure 39: Thermal image of a section of the weld piece after 2 seconds of the third analysis step

A8 – Final concept analysis, heating

A detailed thermal analysis was performed to determine the temperature of the welding wire from the preheating. The analysis incorporates both the preheating from the micro coils and the thermal effect of the Shoulder on the welding wire. The main focus was to investigate the temperature of the welding wire at the micro coil. The temperature of the welding wire just before the Shoulder was also interesting but the analysis result of this could not be regarded as reliable.

Geometry

The analysis was performed with a transient thermal analysis without any dynamics. Since the problem is in fact dynamic, with a horizontally moving Shoulder, this had to be solved through other analysis setups. Figure 40 shows the geometry used. A welding wire is situated inside the Wire Guide as seen in figure 41. The main focus of the analysis was to investigate the wire temperature before the weld. Because of this, the weld piece was not included in the analysis. To solve the dynamic nature of the problem; the wire was divided into segments (see figure 41).

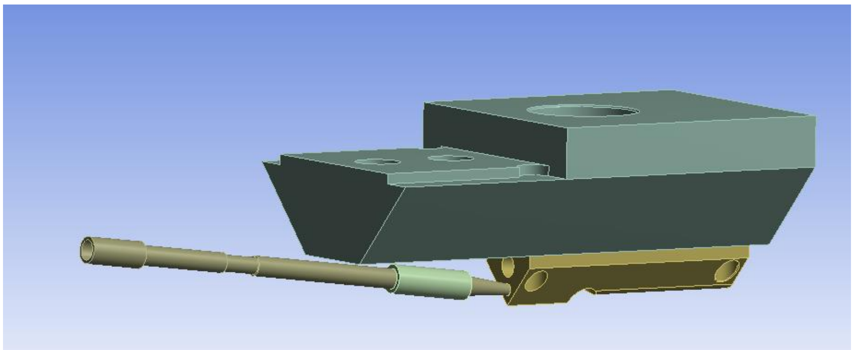

Figure 40: Geometry for the analysis

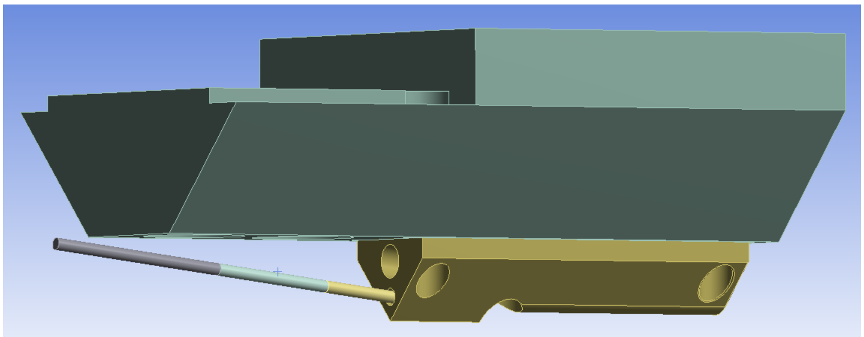

Figure 41: Geometry with the Wire Guide hidden to show the divided welding wire

Boundary conditions and analysis

Since the welding wire is feed the analysis is a dynamic problem. The analysis was performed as a static thermal problem and made use of boundary conditions to solve the dynamic issue. The wire is feed at 1.5 m/min. So the welding wire was divided into 25mm pieces and the with the analysis run time of 1 second. The analysis was performed in 5 steps to be able to get the proper boundary conditions of the welding wire. Using more steps and dividing the welding wire into more parts would give a more accurate analysis. But since the analysis was experimental and since it would take a very long time, this was not done.

The geometry and the analysis were made before the final design of the Wire Guide was complete. The temperature of the welding wire at the micro coil should however be consistent since the diameter of the Wire Guide is the same. The cone of the Wire Guide in this configuration is however longer, so the micro coil is closer to the Shoulder in the real case. The cool down of the welding wire when it moves form the micro coil to the Shoulder should thus be smaller in the real case, compared to this analysis. Because of this, the geometry difference was not regarded as a problem since the temperature of the welding wire before the Shoulder should be higher in the real case compared to this analysis.

The micro coil was modelled as a tube with a power of 175W. The power was modelled by internal heat generation of the tube. The cartridge heater was not included in the analysis. Instead a heat flux consistent with the 175W power of the cartridge was placed in the cartridge heater interface of the Shoulder.

In the first analysis the micro coil and the cartridge heater were run for 10 seconds, which it would be in the real case scenario. This simulated the welding wire being feed into a heated Wire Guide and Shoulder (see figure 42).

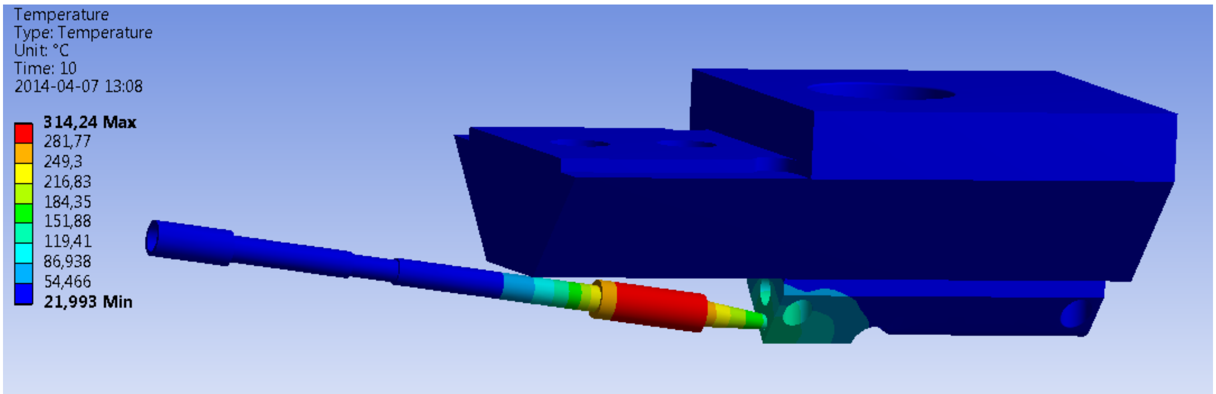

Figure 42: Thermal image after first analysis step

The second analysis set the temperature of the wire to 22°C (see figure 43). This was to simulate a cold welding wire being fed into the heated Wire Guide. Since the analysis only worked to set a boundary condition, it was only run for 0.01 seconds.

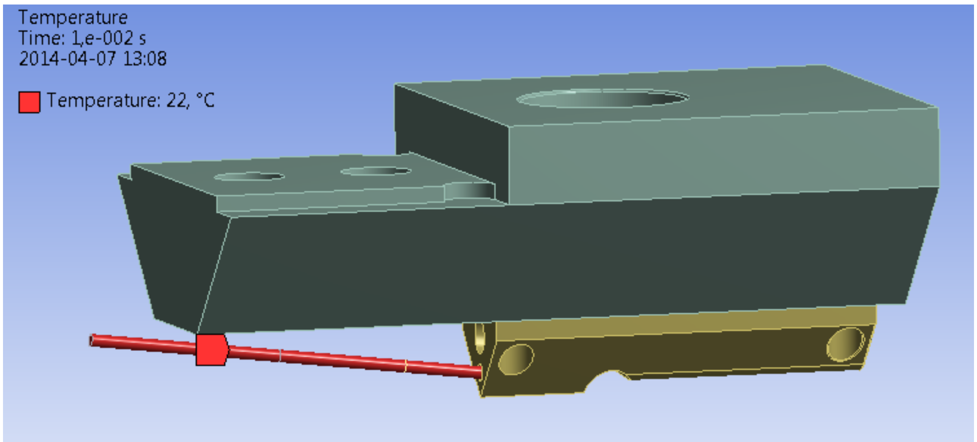

Figure 43: Boundary conditions for the second step of the analysis

The third analysis was run for 1 second, which is the time it takes for the welding wire to pass the micro coil. The micro coil and the cartridge heater were active during the analysis (see figure 44).

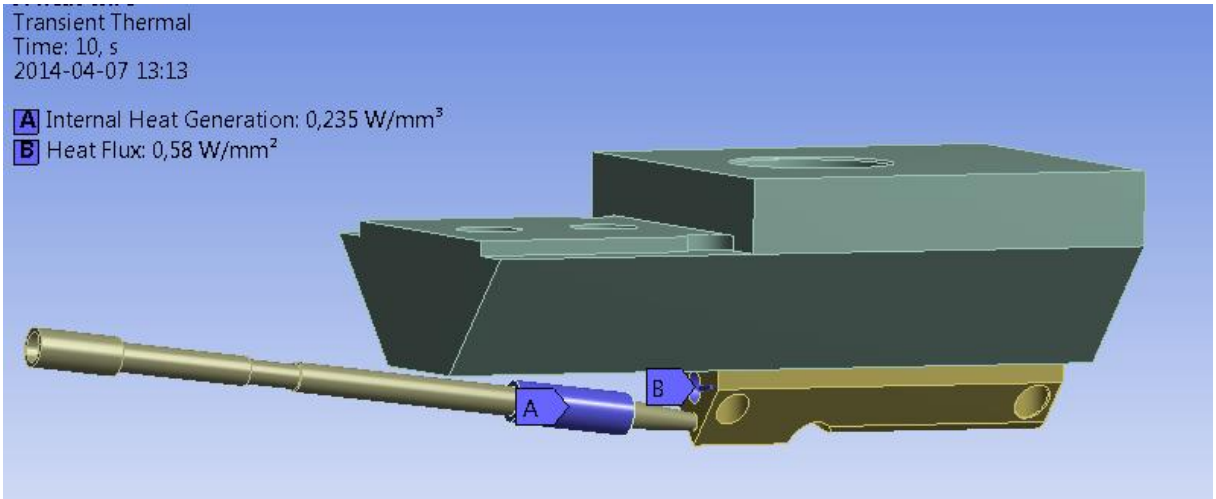

Figure 44: Boundary conditions for the third step of the analysis. Micro coil and cartridge heater are active during the simulation

The result from the third analysis gave the thermal image of the welding wire from the micro coil heating (see figure 45).

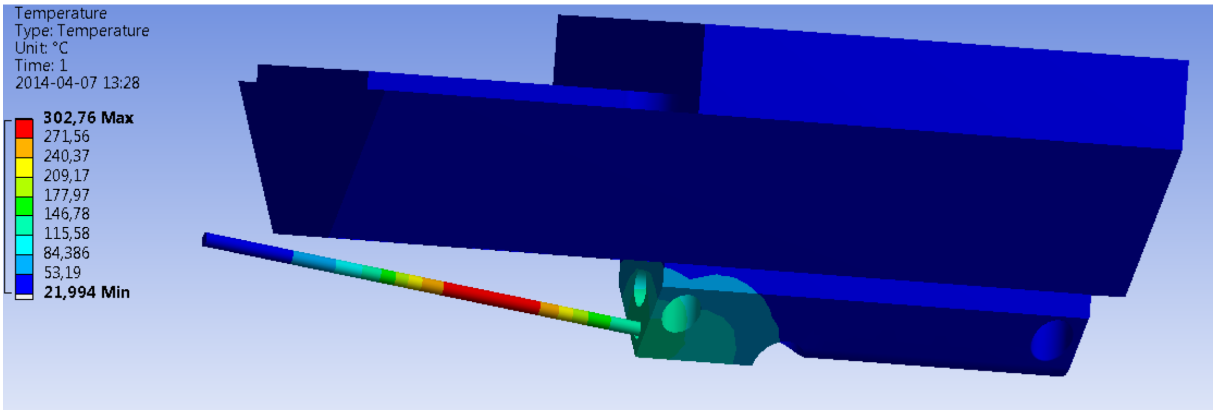

Figure 45: Thermal image of the welding wire after the third step of the analysis

The fourth analysis then served to set the boundary conditions for the fifth. The subsequent welding wire part was given the temperature of the previous one to simulate that the welding wire had been feed 25mm. Since the analysis only worked as set boundary condition, it was only run for 0.01 seconds.

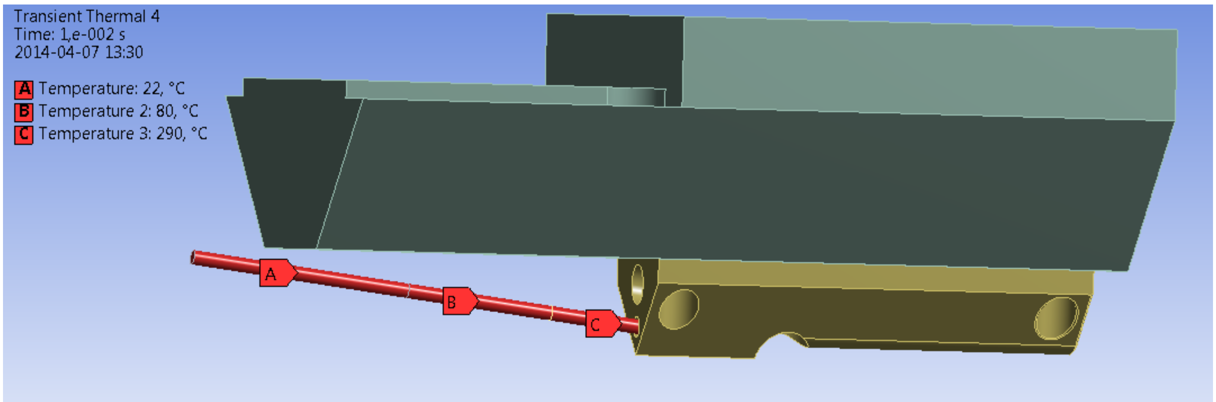

Figure 46: Boundary conditions for the fourth analysis step, each welding wire part was given the mean temperature of the previous one

The fifth analysis was then run with active micro coil and cartridge heater, similar to the third analysis. The welding wire had the boundary conditions of the fourth analysis, which simulated that the welding wire had been feed 25mm after the previous heating. The resulting thermal image of the welding wire can be seen in figure 47.

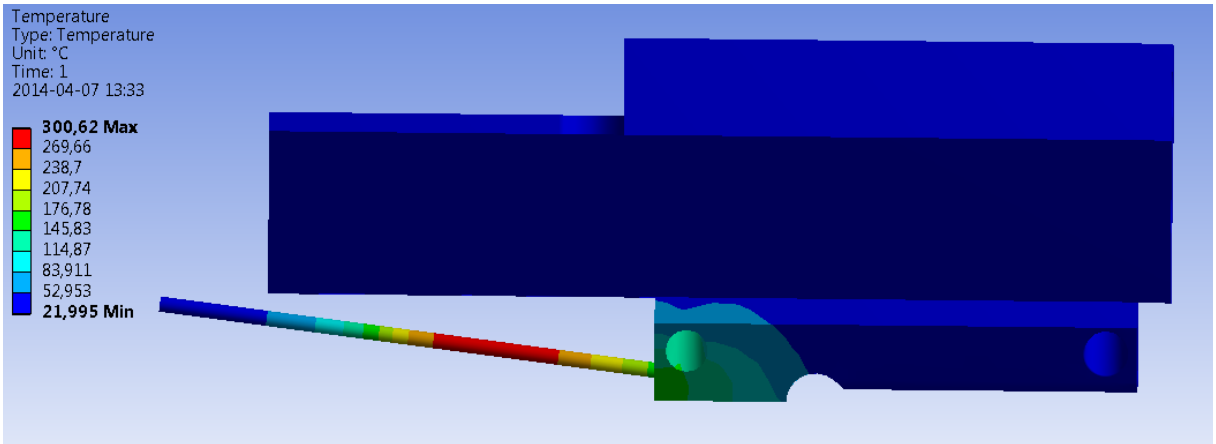

Figure 47: Thermal image of the welding wire after the fifth analysis step

The analysis showed that the welding wire would be preheated by the micro coil to approximately 300°C. This was supported by both the third and the fifth analysis. Although this is a dynamic problem that is being simulated by a static analysis the result should be quite accurate since the contact time to the micro coil is the same as in the real case. A higher resolution with the welding wire divided into smaller parts would of course give a more accurate result. The simulated dynamics of the analysis showed that the welding wire would then be cooled down to approximately 170°C. This result is however vague since the thermal image of the Shoulder is unclear. Neither the thermal weld zone nor the cool weld piece is included in the analysis. This could either lead to a higher or a lower welding wire temperature before the Shoulder. The temperature of the welding wire at the micro coil and before the Shoulder can be seen in table 8.

Table 8: Welding wire temperature after micro coil heating and before the Shoulder

Part	Temperature [°C]
Welding wire after micro coil	300
Welding wire before Shoulder	170

B – Screening calculation

A simple calculation to get a picture over the amount of power available in the heating concepts and the amount of power required the heat the weld piece and welding wire.

Cartridge heater

The most capable cartridge heater that could be fitted in the Shoulder was a cartridge heater from Backer BHV AB. The cartridge heater has a diameter of 6mm, a length of 25mm and a power output of 175W (Backer BHV AB, 2014).

The Shoulder could hold one cartridge heater without negatively influencing any other functions or posing to large manufacturing difficulties. This would lead to an available power of 175W in the Shoulder.

Heating cables

The heating cables with the largest power output found were also from Backer BHV AB. The heating cables have a cross section area of 14.2x5.2mm and a power output of 75W/m (Backer BHV AB, 2014).

The heating cables were larger than the cartridge heater. The maximum length of heating cables that could be fitted in the Shoulder was 60mm. This setup was still not optimum since it posed manufacturing difficulties of the Shoulder. The available power in the heating cables was 4.5W (see equation 1).

$$P = 75 * 0.06 = 4.5\ W \tag{1}$$

Heating power needed

To get a view of the amount of power needed to heat the weld piece and the welding wire to 300^{o}C, a calculation was performed. The calculation does not represent a real welding scenario and is highly simplified. The amount of material that needs to be heated was estimated by calculating the area that passed over the Shoulder each second (see equation 5). The power needed to heat the weld piece and the welding wire to 300^{o}C was calculated to be 1441.15W (see equation 10)

$$Reletive\ speed\ of\ weld\ piece\ and\ Shoulder:$$
$$v_{weld\ piece} = 1.5[m/mim] = 0.025[m/s]$$
$$Cros\ section\ area\ of\ the\ welding\ wire:$$
$$A_{wire} = \pi r^2 = \pi * \frac{2.4^2}{4} = 4.5 * 10^{-6}[m^2] \tag{2}$$
$$Cross\ section\ area\ of the\ weld\ piece\ that\ needs\ to\ be\ heated:$$
$$A_{weld\ piece} = 75 * 10^{-6}[m^2] \tag{3}$$
$$The\ total\ cross\ section\ area\ can\ be\ calculated\ by\ adding\ the\ areas\ from\ 2\ and\ 3:$$
$$A_{tot} = A_{wire} + A_{weld\ piece} = 4.5 * 10^{-6} + 75 * 10^{-6} = 79.5 * 10^{-6}[m^2] \tag{4}$$
$$Wire\ feeding\ speed:$$

$$v_{wire} = 1.5[m/mim] = 0.025[m/s]$$
$$Welding\ wire\ volume\ flow:$$
$$v_{weld\ piece} = v_{wire} = v$$
$$V = A_{tot} * v = 79.5 * 10^{-6} * 0.025 = 2 * 10^{-6}[m^3/s] \quad (5)$$
$Specific\ heat\ coeficient\ for\ aluminium$ (Sundström, 2008)
$$C_p = 960[J/(kg * K)] \quad (6)$$
$Density\ for\ aluminium$ (Sundström, 2008)
$$\rho = 2700[kg/m^3] \quad (7)$$
$$Wanted\ temperature\ temperature\ rise:$$
$$\Delta K = 300 - 22 = 278[K] \quad (8)$$
$The\ expression\ from\ 6\ can\ be\ rewritten. By\ solving\ the\ energy\ and\ using\ mass\ flow\ instead\ of\ mass\ the\ power\ can\ be\ calculated:$
$$P = C_p * V * \rho * \Delta K \quad (9)$$
$The\ heating\ power\ needed\ can\ now\ be\ calculated\ with\ the\ results\ from\ 4 - 8\ together\ with\ equation\ 9:$
$$P = C_p * V * \rho * \Delta K = 960 * 2 * 10^{-6} * 2700 * 278 = 1441.15[W] \quad (9)$$

C – Matlab scripts

This appendix shows the Matlab scripts used in the thesis. Some values have been changed in the scripts due to confidentiality.

C1 – Probe, Shoulder and Shoulder Holder dimensions

This script calculated dimensions for the Probe, Shoulder and Shoulder Holder. The script ensured a perfect fit while still conforming to preconditions and fixed measures.

```
% Program for calculating Probe, Shoulder and Shoulder Holder
dimensions
% Depending on various changeable parameters
clear all
close all
clc
% Input parameters
mt = 5; % Material thickness
ia = 45; % Weld insert angle
prr = 4; % Probe radii weld
prrg = 4.5; % Probe radii slide
or= prrg-prr; % Radii between weld and slide
o = 0.5; % Overlap
pa = 60; % Probe angle
pr = 2; % Probe front radii
wd = 2.4; % Wire diameter
wa = 7; % Wire insert angle
dwg = 1; % Distance from bottom of wire to edge (given from
ESAB)
dww = dwg + wd/cosd(wa)/2; % Distance from wire centre to edge
bh = 15; % Bearing height
bor = 14; % Bearing outer radii
psch = 8; % Probe Shoulder contact height
et =1; % Extra thread above wire
pte = dwg+wd/cosd(wa)+et; % Probe threaded height from edge
des = (sind(180-ia-pa/2)/sind(pa/2))*(mt/2+o); % Distance from
edge to prolongded Probe edge
dsse = prr/tand(pa/2)-des; % Distance from start of straight
thread to edge
psc = pte+or+psch+2; % Probe start cone height from edge
sh = 24; % Shoulder height
ks = psc-2; % Cone start, distance from edge to start of cone
skh = sh - ks; % Cone height
shh = 40; % Shoulder Holder height
shkh = shh-8-(bh-2); % Shoulder Holder cone height
ki = (bor*skh + prrg*shkh)/(skh+shkh) ; % Cone interface radii
between Shoulder and Shoulder Holder
pkh = shkh+skh ; % Cone height of Probe
pbh = bh-1 ; % Probe bearing height
```

```
stl = pte-dsse; % Hight of straight Probe before cone
angle = atand((bor-prrg)/pkh); %Angle of Probe, Shoulder and
sh
% This gives exact measures to get a perfect fit. Measures has
to be
% rounded before manufacturing.
```

C2 – Welding of different material thicknesses

A generic script for calculating Probe and Shoulder dimensions, with input values of material thickness and Probe diameter.

```
% Calculation of new Probe and Shoulder dimensions for welding
% different material thicknesses
clc
clear all
% REFERENCE MEASURES
st=5; % Material thickness
D=8; % Weld diameter
SD=9; % Slide diameter
SL=10; % Slide length
STL= 13.8; %Slide straight + thread length
SSL=12.918; %Shoulder straight length from edge
PSL=SSL+2; %Probe straight length form edge
%% XXmm material
clc
% INPUT VALUES
nt=12; % Material thickness
DN= 11; % Probe diameter
A= DN+1; % Slide diameter (Probe and Shoulder)
% Determining Probe tip radii
if nt<3
    D=1;
elseif (3<=nt)&&(nt<=8)
    D=2;
elseif 8<nt
    D=3;
end
% Determining weld fillet for Shoulder
if nt<3
    E=1;
elseif (3<=nt)&&(nt<=4)
    E=4;
elseif 4<nt
    E=5;
end
% CALCULATIONS
% Removed material thickness
t=st-nt;
```

```
% Depth change from different Slide diameter
dd=(SD-A)/2/tand(17.5);
% Depth change from different material thickness
LD= (t/2)*sind(105)/sind(30);
% Depth change from different Probe diameter (to get 0,5mm
overlap)
ED = tand(60)*(D-DN)/2;
% Measure from Shoulder angle to the material edge
NSSL = SSL-dd;
% Measure from Probe angle to the material edge
NPSL = PSL -dd;
% New slide lengths, calculated to have a small distance to
the material
C = floor(NPSL - A/2);
% New length of slide length + thread length
B =STL - dd + ED -LD;
% Round NSTL to one decimal
B=round(B*10)/10;
```

D – Drawings

This appendix contains all production drawings for the developed parts for part 1 and 2 of the project. All critical measures have been blurred due to confidentiality.

D1- Drawings for part 1

This chapter contains all production drawings for the developed parts for Part 1. The BOM for the assembly drawing on the next page is shown below.

Pos.	Quantity	Article Number	Part
001	1	-	Spindle housing
002	1	-	Mounting plate
003	1	-	Arm
004	1	-	Probe Holder
005	1	-	Shoulder-holder
006	1	-	Shoulder
007	1	-	Bearing
008	1	-	Wire Guide conical
009	1	-	Wire Guide straight
010	1	-	Probe
011	1	-	Hydraulic cylinder
012	1	-	Plastic tube
013	1	-	Wire connector
014	1	-	Rail
015	2	-	Slider
016	1	-	Wire feeder motor
017	1	-	Leveller
018	1	-	Mounting plate feeder
019	1	-	L-profile
020	1	-	Wire spool holder
021	1	-	Wire spool
022	1	-	Pincher
023	13	-	M10 Hexagon head screw
024	2	-	M16 Tension screw Weldon
025	2	-	M4 Hexagon socket head cap screw
026	2	-	M12 Hexagon socket head cap screw
027	2	-	M4 Hexagon head screw
028	4	-	M10 Hexagon head screw
029	4	-	M8 Hexagon head screw
030	8	-	M6 Hexagon socket head cap screw
031	8	-	M12 Hexagon socket head cap screw
032	4	-	M10 Hexagon socket head cap screw
033	12	-	M10 washer
034	4	-	M8 washer

2007-xx-xx

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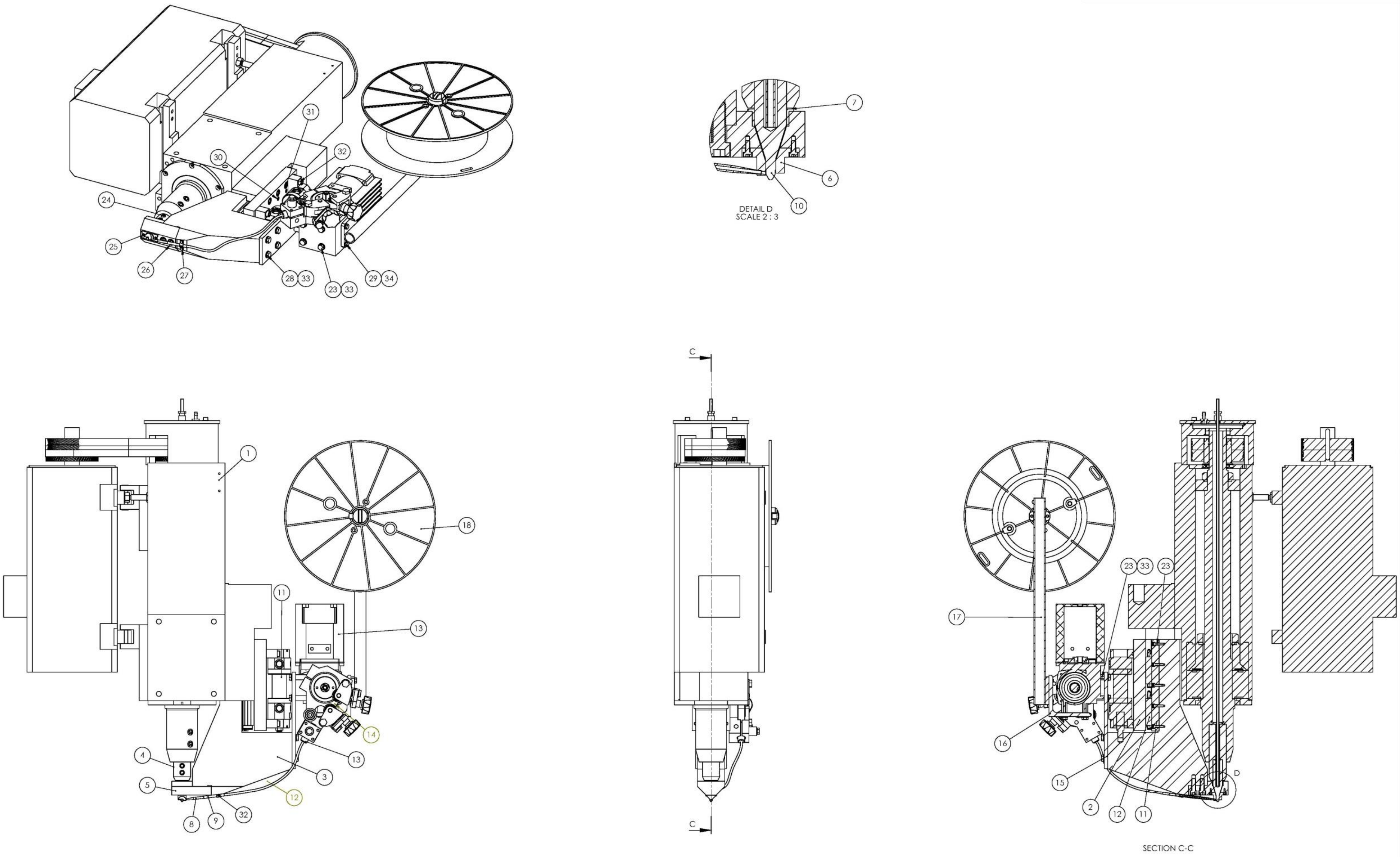
ESAB WELDING EQUIPMENT AB

ESAB	Stationary shoulder Sammanställningssritning						XXX XXX
	.		Type .			Scale 1:5	Code 20
Year 2014	.	Design checked by .	Accepted for prod.by .	Drawing checked by .	Drawn by .	V indicates R_a in µm	Sheet 1 (1) Revision 1



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Tolerances for untoleranced dimensions acc. to ISO 2768-1

Model / Medium

Painting No. .

Compare No. .

SolidWorks

Release date: 2007-xx-xx

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ESAB WELDING EQUIPMENT AB

ESAB®	PROBE							
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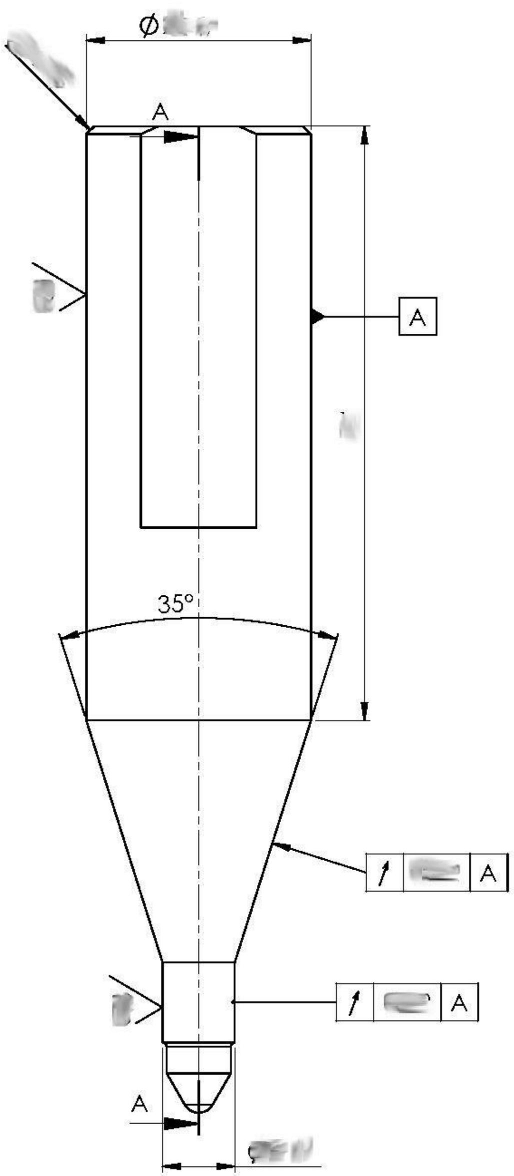
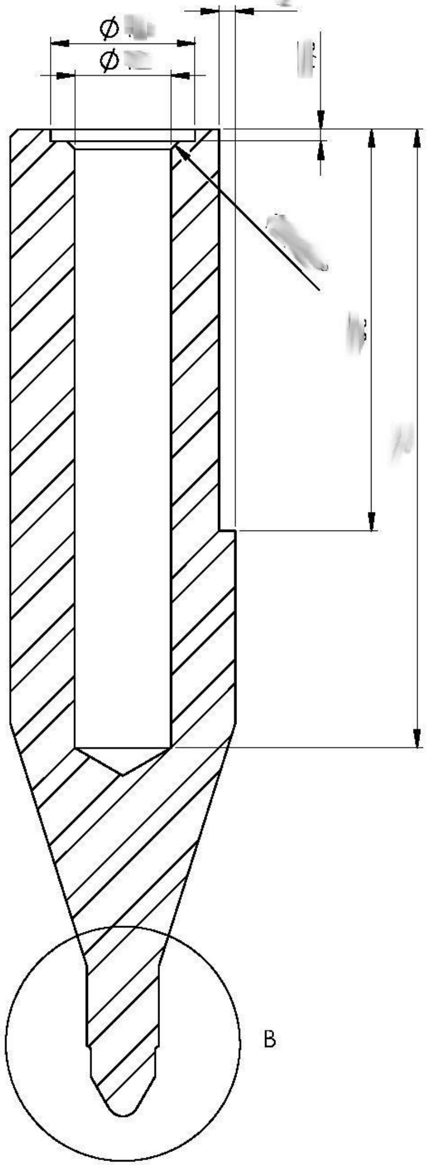
2014	xx	.	.					Rev. x

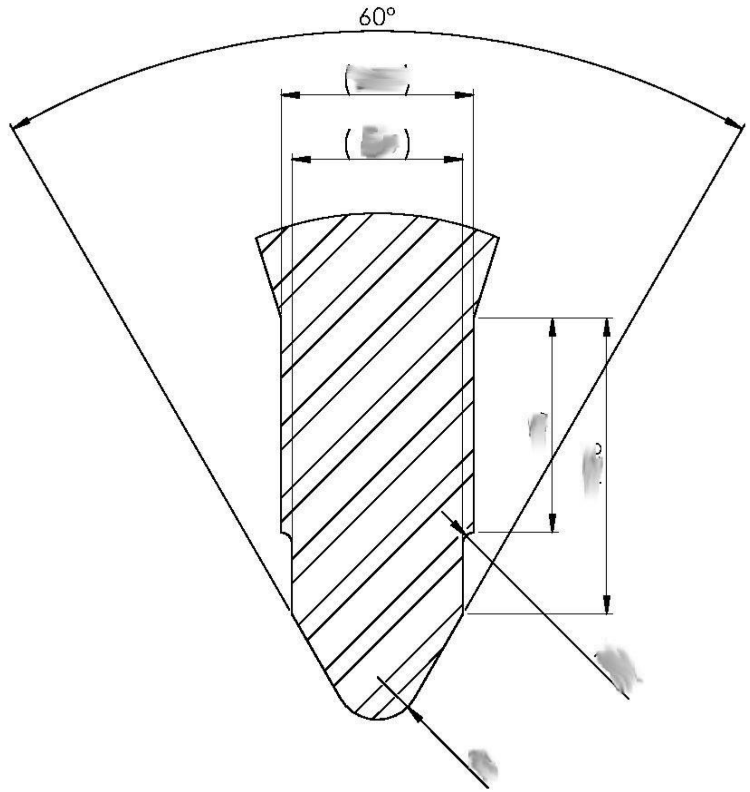
-881	-880	Pos no.	Designation	Article number	Material Quality	Notation
			Probe		QRO 90	Stång, D=

QRO 90, härdat till HRC 47-49





SECTION A-A



DETAIL B
SCALE

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Tolerances for untoleranced dimensions acc. to ISO 2768-1	Painting No. .
	Compare No. .

SolidWorks [illegible]

Release date: 2007-xx-xx

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ESAB WELDING EQUIPMENT AB

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Year 2014	Week xx	Design checked by .	Accepted for prod. by .	Drawing checked by	Drawn by	V indicates R_a in µm .	Sheet 2 (4) Rev. x
-881	-880	Pos no.	Designation	Article number	Material Quality	Notation	
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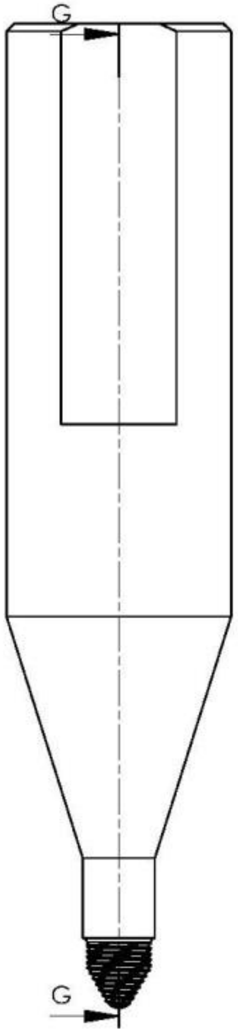
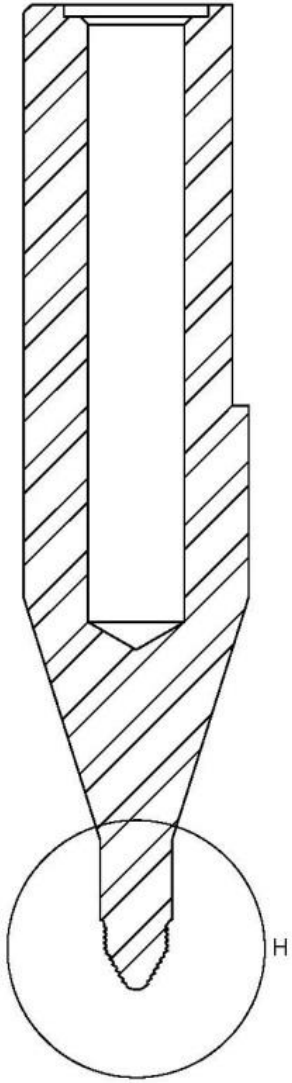
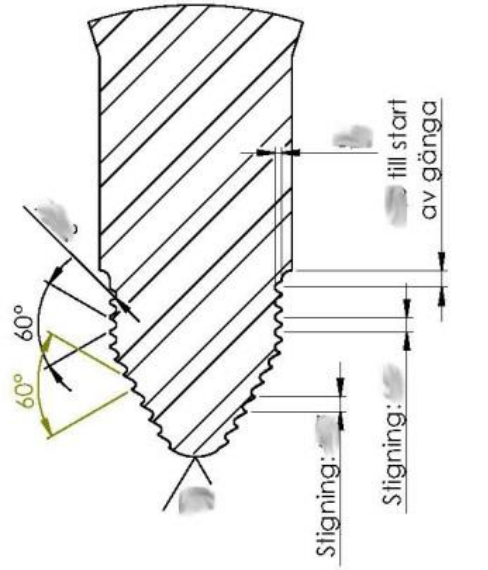




SECTION G-G

Bearbeta med [illegible] mm stigning och vänstergänga med verktyget vinkelrätt mot centrumlinjen. Med gänga enligt dimensioner



DETAIL H
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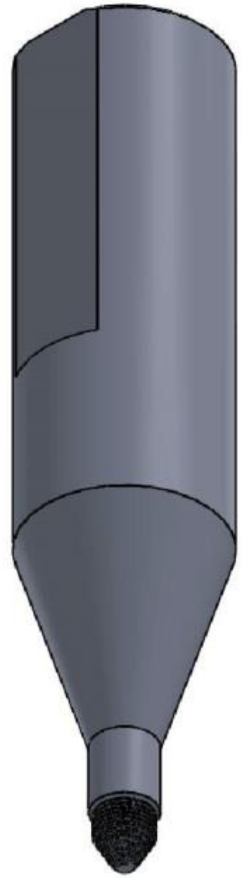

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SolidWorks

Release date: 2007-xx-xx

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ESAB WELDING EQUIPMENT AB

ESAB	PROBE						
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	.			Type .			Sheet 3 (4)
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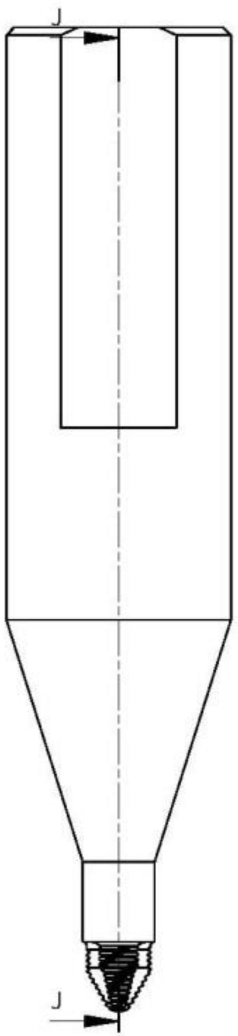
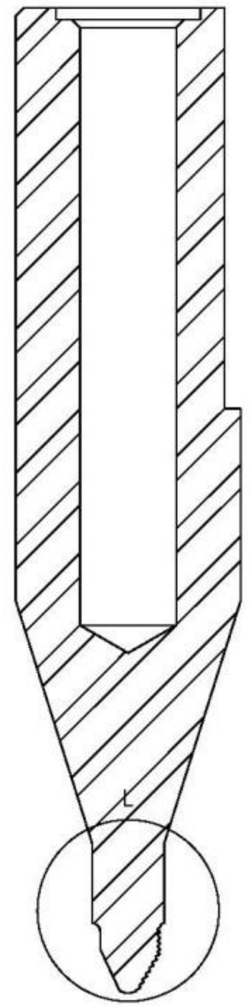
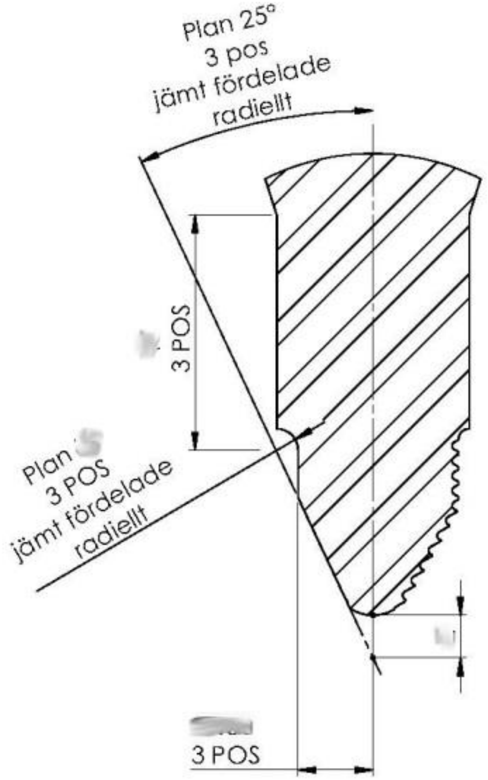
-881	-880	Pos no.	Designation	Article number	Material Quality	Notation	
			Probe		QRO 90	Stång, D=	

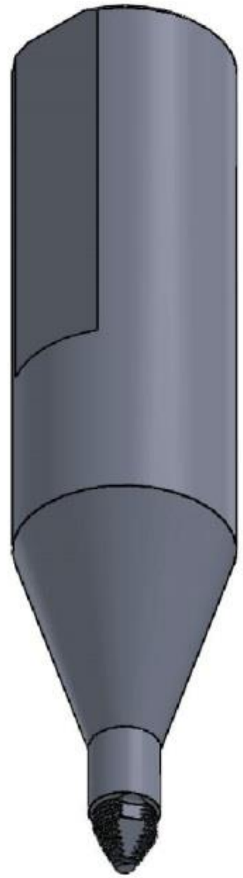




SECTION J-J



DETAIL L
SCALE



Alteration No.	Alteration	sign., year, month entered
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Tolerances for untoleranced dimensions acc. to ISO 2768-1

Painting No. .

Compare No. .

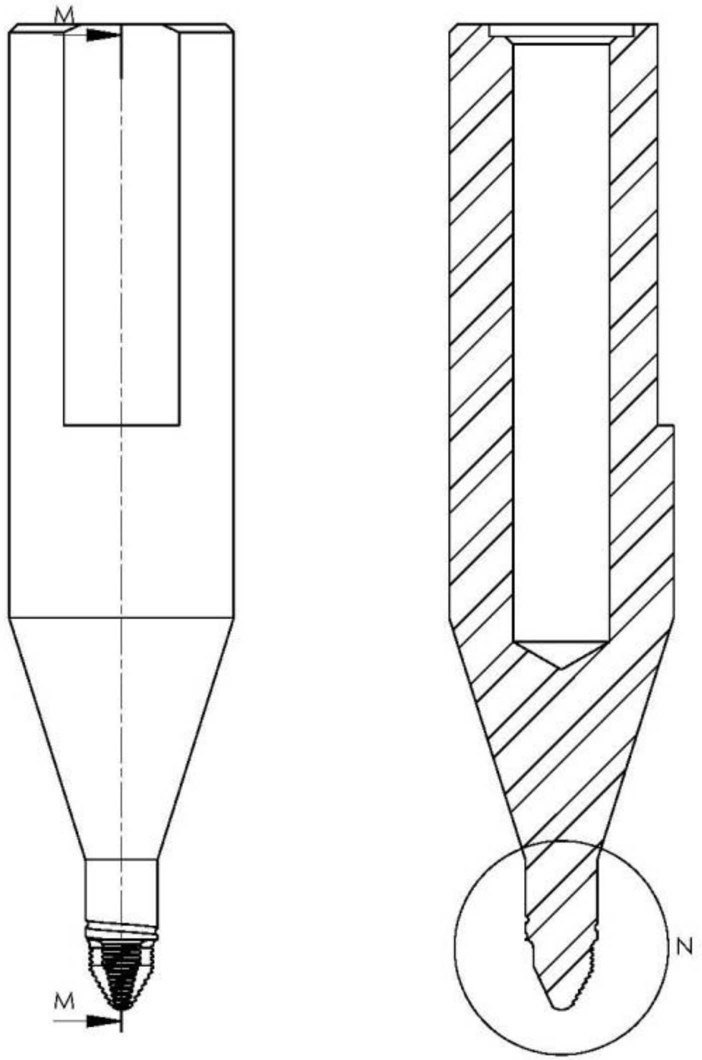
SolidWorks

Release date: 2007-xx-xx

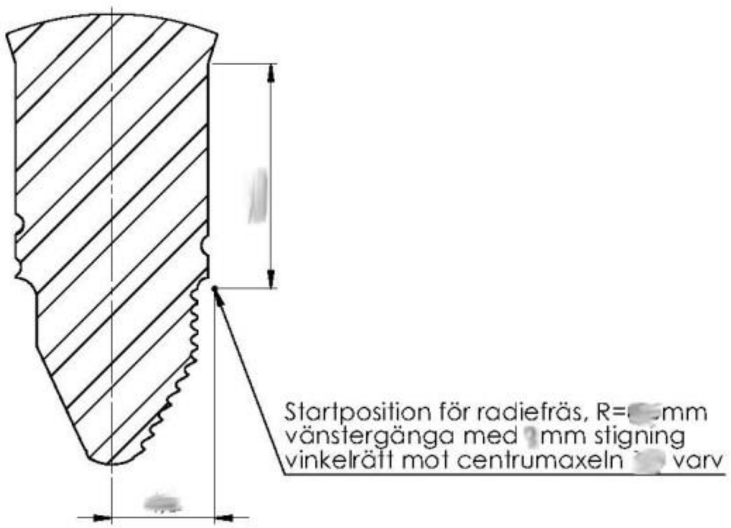
ESAB®

PROBE							
Tillverkningssteg 4							
.				Type .		Scale	Code 20
Year 2014	Week xx	Design checked by .	Accepted for prod. by .	Drawing checked by	Drawn by	V indicates R_a in µm .	Sheet 4 (4) Rev. x

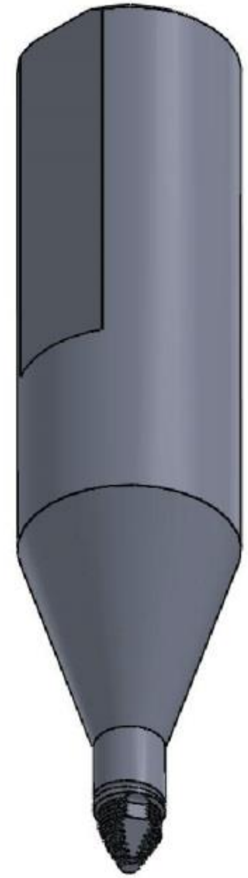
-881	-880	Pos no.	Designation	Article number	Material Quality	Notation
			Probe		QRO 90	Stång, D=



SECTION M-M



DETAIL N
SCALE



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Alteration No.	Alteration	sign., year, month entered

Tolerances for untoleranced dimensions acc. to ISO 2768-1	Painting No. .
	Compare No. .

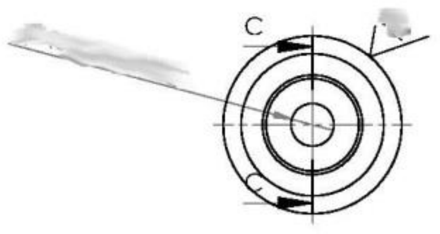
SolidWorks

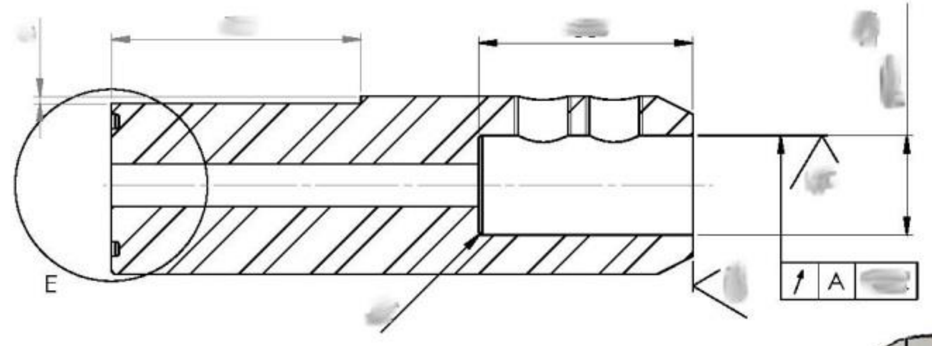
Release date: 2007-xx-xx

PROBE HOLDER

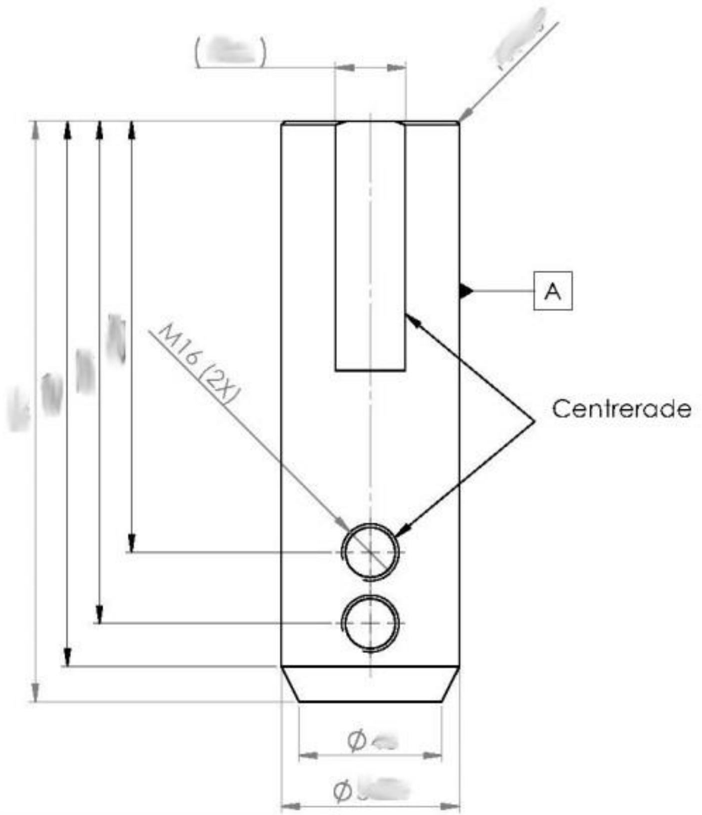
Year	Week	Design checked by	Accepted for prod. by	Drawing checked by	Drawn by	Type	Scale	Code 20	Sheet 1 (1) Rev. x
2014	xx	.	.			.	V indicates R_a in µm .		

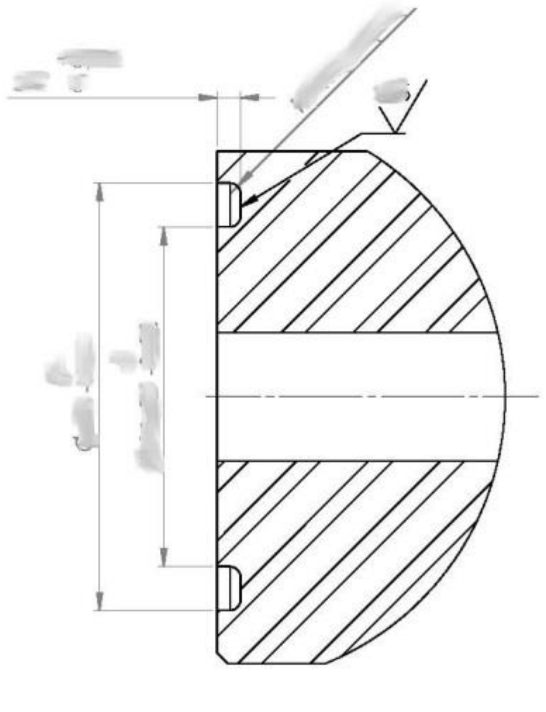
-881	-880	Pos no.	Designation	Article number	Material Quality	Notation
			Probe holder		S355J2	Stång, D=





SECTION C-C





DETAIL E
SCALE

Vikt:

Alteration No.	Alteration	sign., year, month entered
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Tolerances for untoleranced dimensions acc. to ISO 2768-1

Painting No. .

Compare No. .

SolidWorks

Release date: 2007-xx-xx

ESAB®

SHOULDER-HOLDER

Skärritning

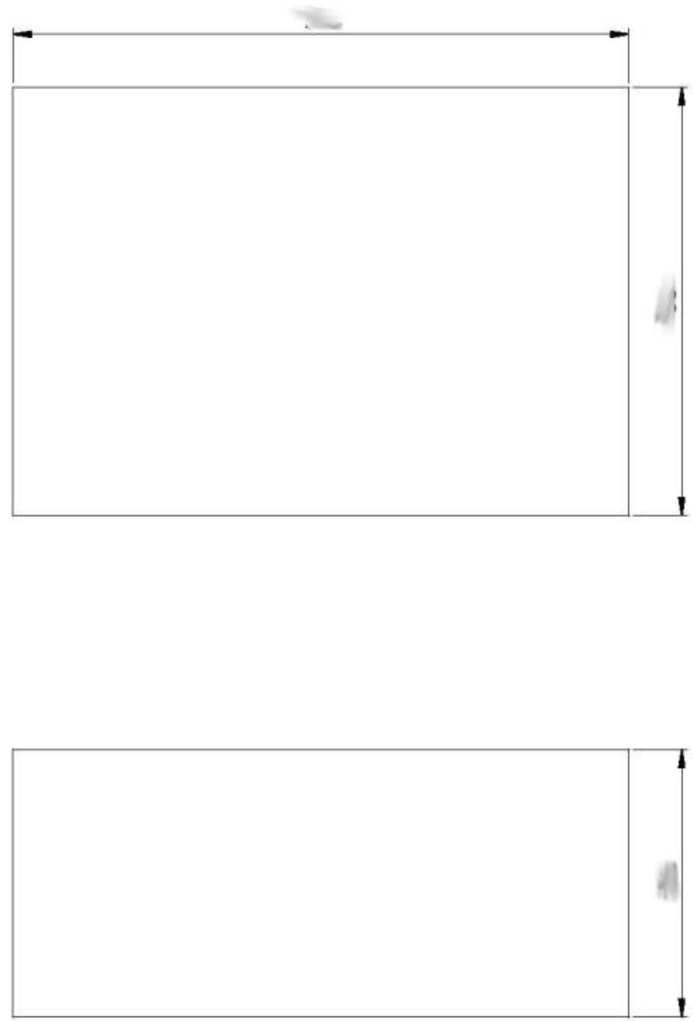
Year	Week	Design checked by	Accepted for prod. by	Drawing checked by	Drawn by	Type	Scale	Code
2014	xx	.	.			.		20

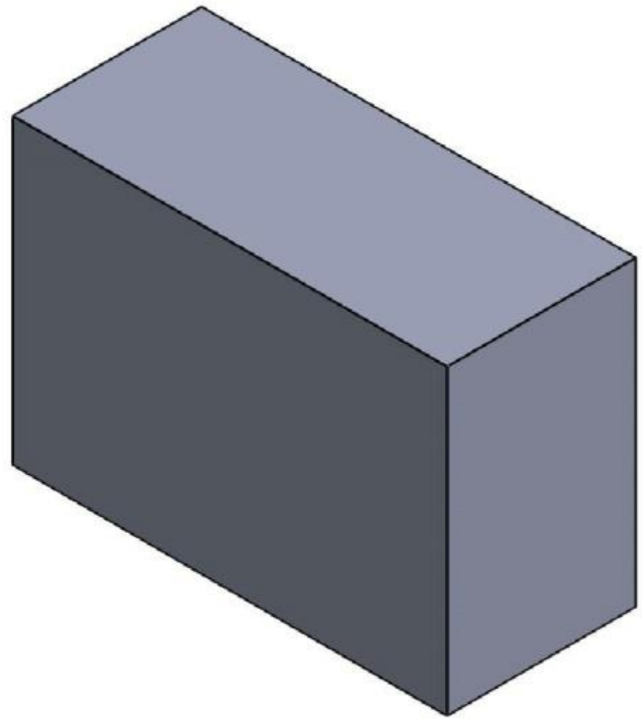
V indicates R_a in µm .

Sheet 1 (2)

Rev. x

-881	-880	Pos no.	Designation	Article number	Material Quality	Notation
			Shoulder-Holder		S355J2	Plåt, T=





Vikt:

Alteration No.	Alteration	sign., year, month entered
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Tolerances for untoleranced dimensions acc. to ISO 2768-1

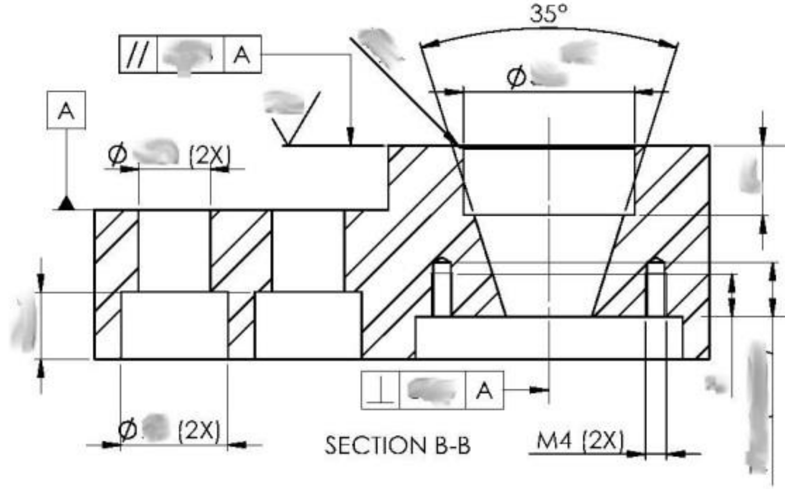
Painting No. .

Compare No. .

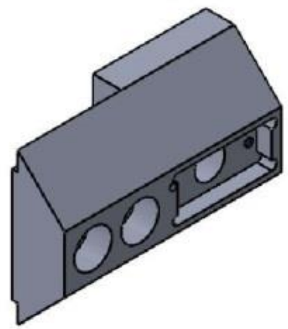
SolidWorks

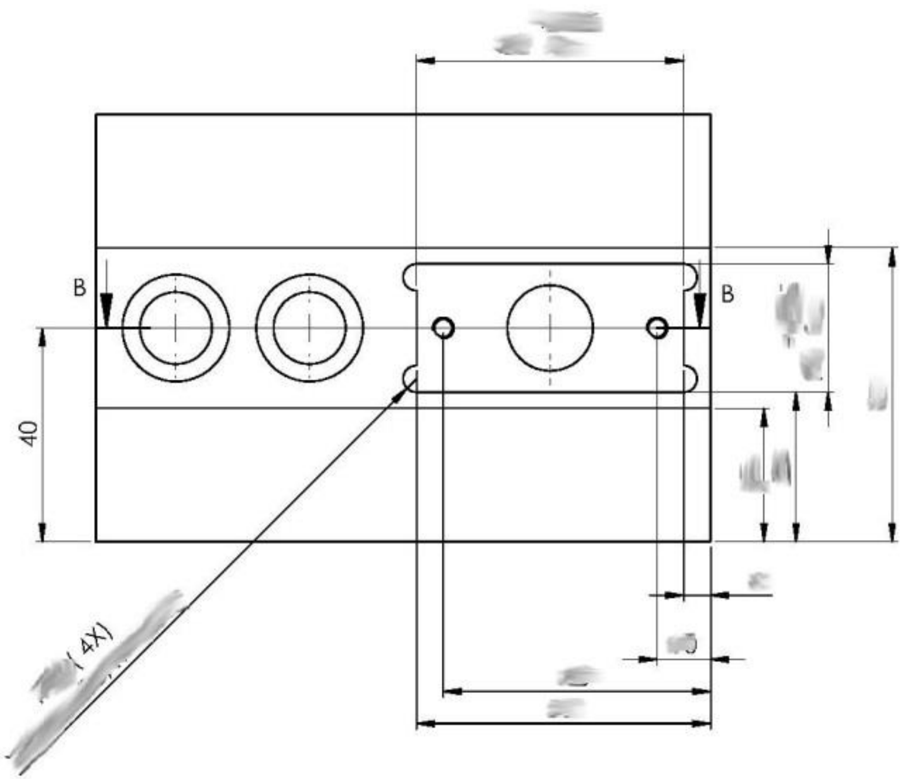
Release date: 2007-xx-xx

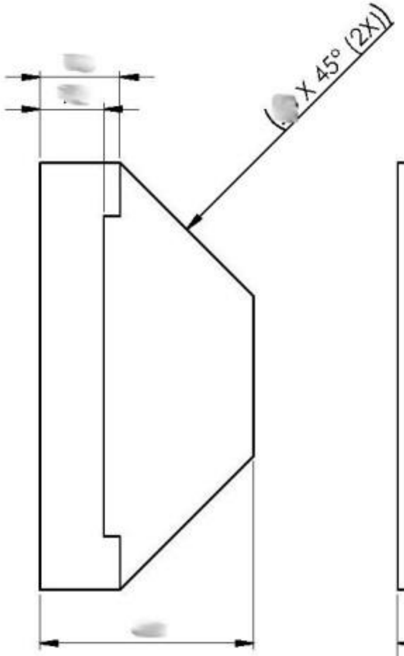
ESAB®	SHOULDER-HOLDER						
	Bearbetningsritning						
	.			Type .		Scale	Code 20
Year 2014	Week xx	Design checked by .	Accepted for prod. by .	Drawing checked by	Drawn by	V indicates R_a in µm .	Sheet 2 (2) Rev. x
-881	-880	Pos no.	Designation	Article number		Material Quality	Notation
			Shoulder-Holder			S355J2	Plåt, T=

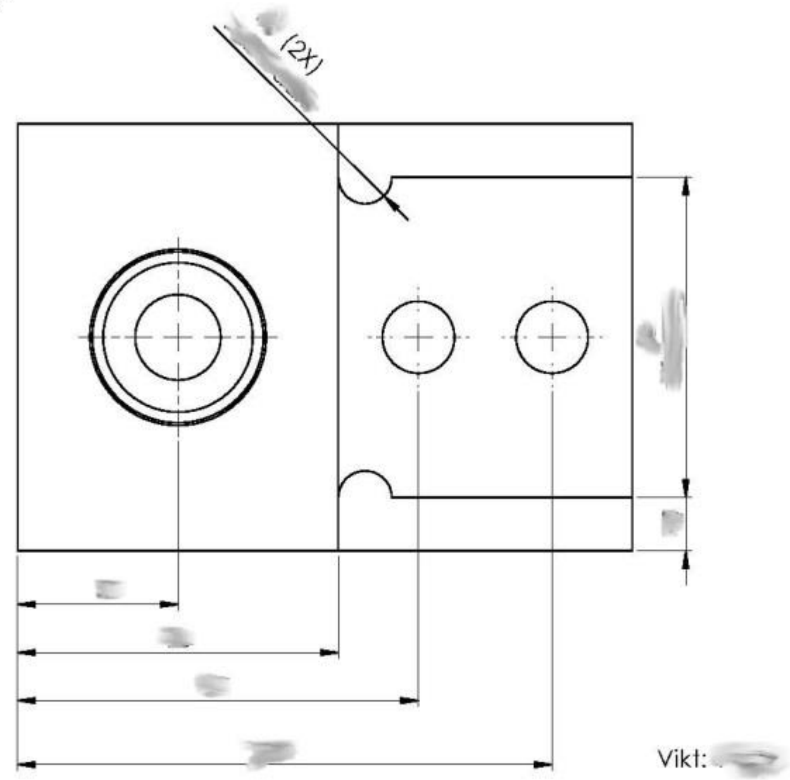


Bearbetade ytor
Ra , gäller ej
borrade hål









Vikt:

Alteration No.	Alteration	sign., year, month entered
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Tolerances for untoleranced dimensions acc. to ISO 2768-1

Painting No. .

Compare No. .

SolidWorks

Release date: 2007-xx-xx

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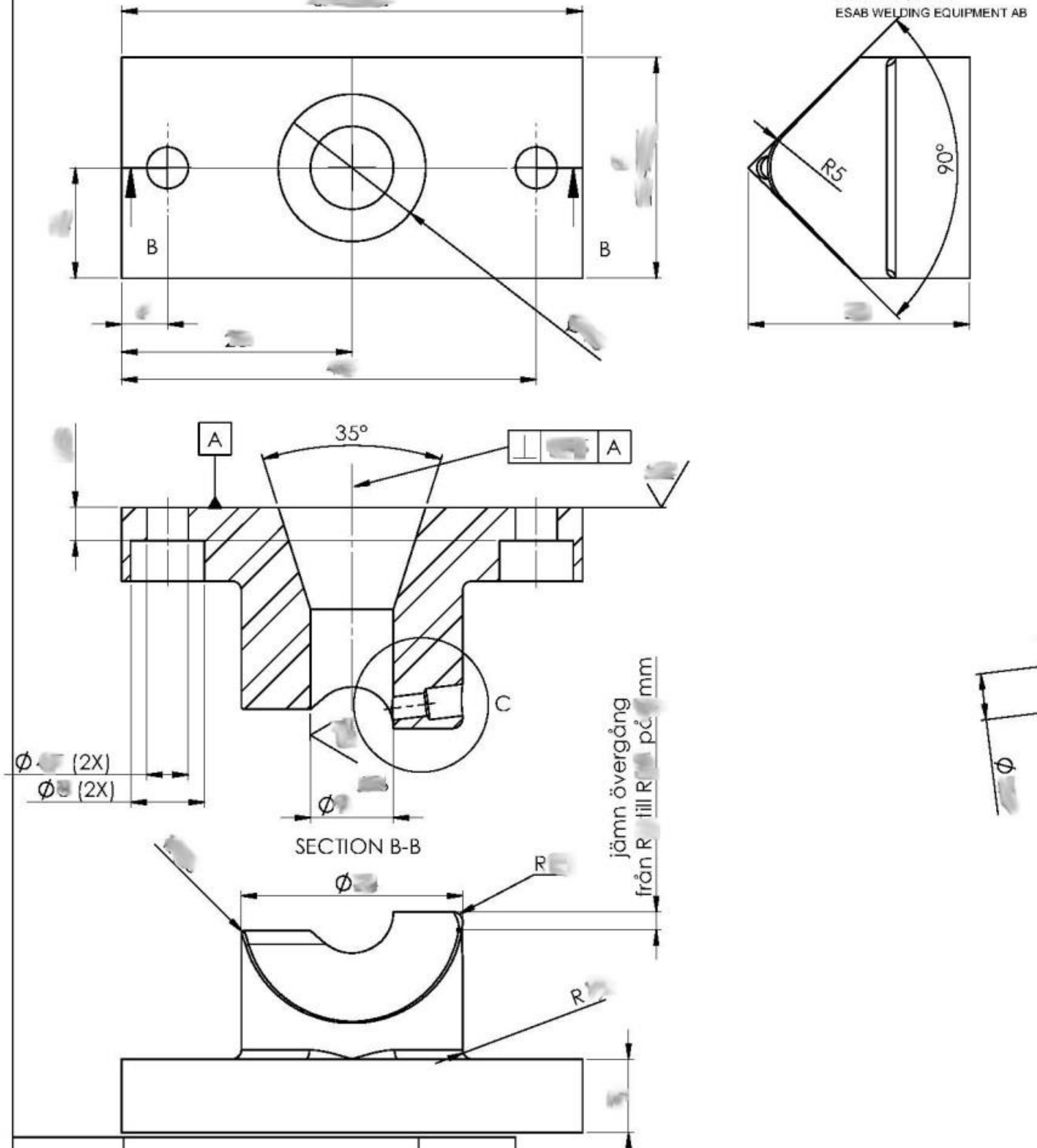
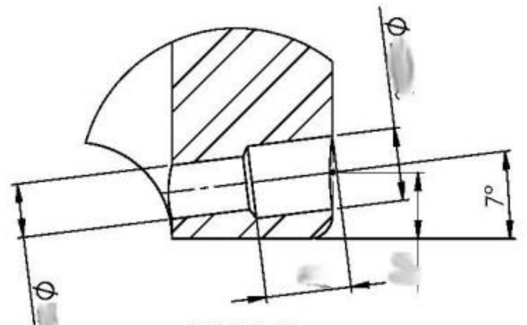
ESAB WELDING EQUIPMENT AB

ESAB		SHOULDER					
Year 2014	Week xx	Design checked by	Accepted for prod. by	Drawing checked by	Drawn by	Type . / V indicates R_a in µm . / Scale	Code 20 / Sheet 1 (1) / Rev. x
-881	-880	Pos no.	Designation	Article number		Material Quality	Notation
			Shoulder			QRO 90	T=

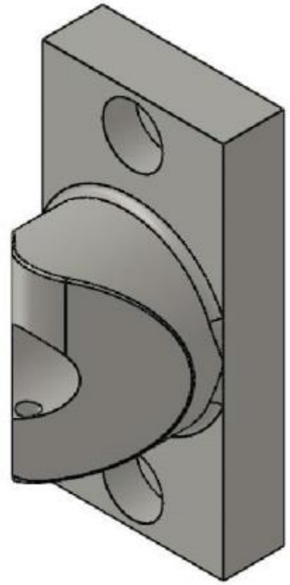
QRO 90, härdat till HRC 47-49

Bearbetade ytor Ra gäller ej borrade hål





DETAIL C
SCALE



Vikt:

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Alteration No.	Alteration	sign., year, month entered

Tolerances for untoleranced dimensions acc. to ISO 2768-1

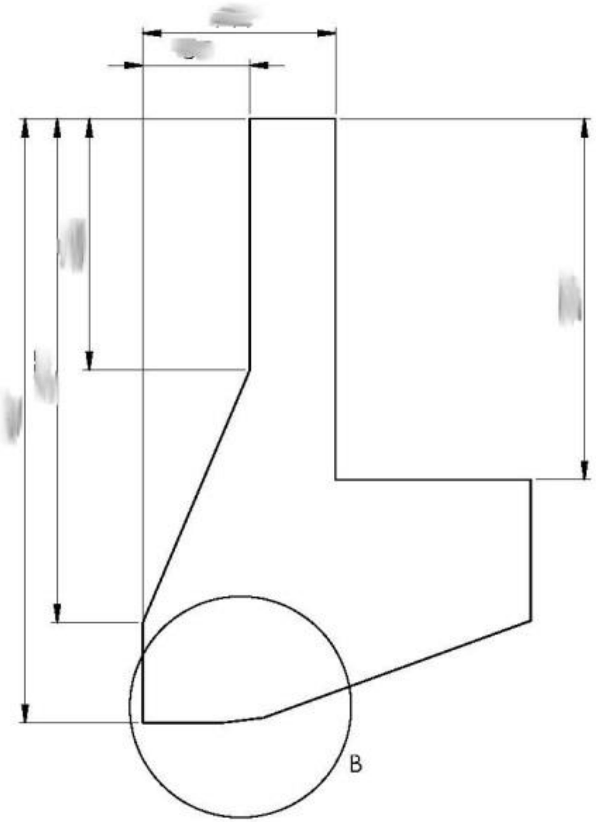
Painting No. .

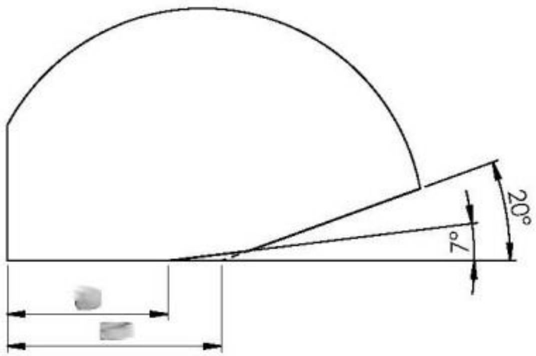
Compare No. .

SolidWorks

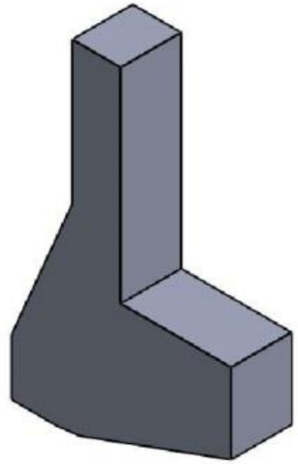
Release date: 2007-xx-xx

ESAB®	ARM						
	Skärritning						
				Type .		Scale	Code 20
Year 2014	Week xx	Design checked by .	Accepted for prod. by .	Drawing checked by	Drawn by	V indicates R_a in µm .	Sheet 2 (2) Rev. x
-881	-880	Pos no.	Designation	Article number		Material Quality	Notation
			Arm			S355J2	Plåt, T=





DETAIL B
SCALE



Vikt:

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Alteration No.	Alteration	sign., year, month entered

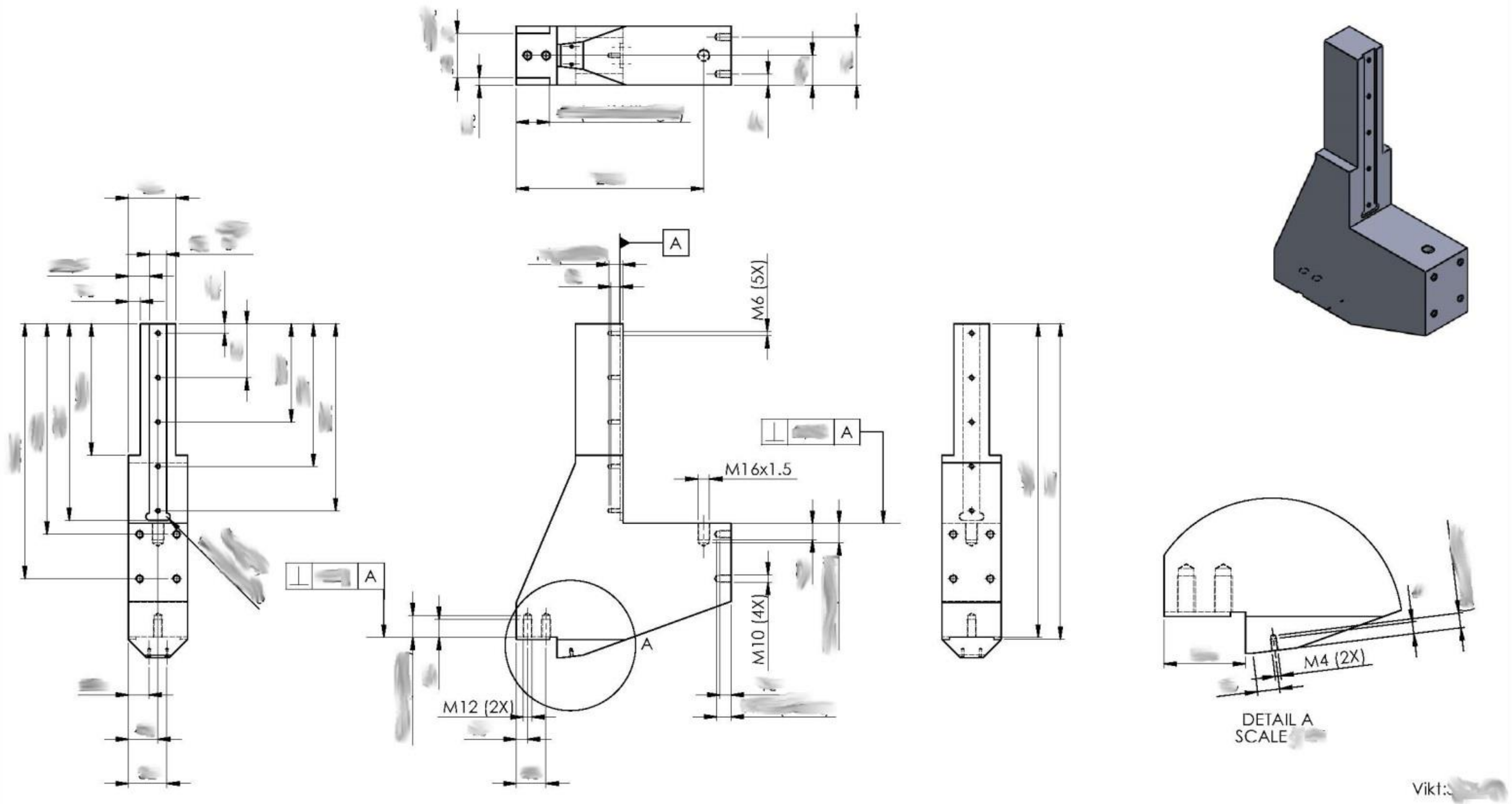
Tolerances for untoleranced dimensions acc. to ISO 2768-1	Painting No. .
	Compare No. .

SolidWorks

Release date: 2007-xx-xx

ESAB®

ARM							
Bearbetningsritning							
.				Type .		Scale	Code 20
Year 2014	Week xx	Design checked by .	Accepted for prod. by .	Drawing checked by	Drawn by	V indicates R_a in µm .	Sheet 1 (2) Rev. x
-881	-880	Pos no.	Designation	Article number	Material Quality	Notation	
			Arm		S355J2	Plåt, T	



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Alteration No.	Alteration	sign., year, month entered

Tolerances for untoleranced dimensions acc. to ISO 2768-1

Painting No. .

Compare No. .

SolidWorks

Release date: 2007-xx-xx

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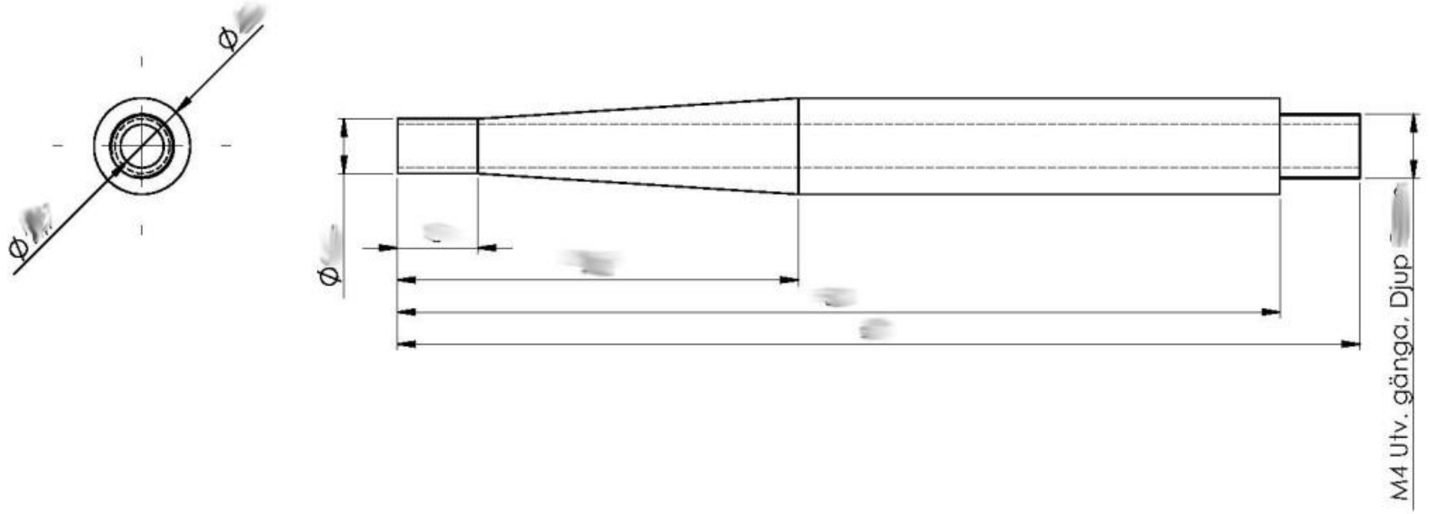
ESAB WELDING EQUIPMENT AB

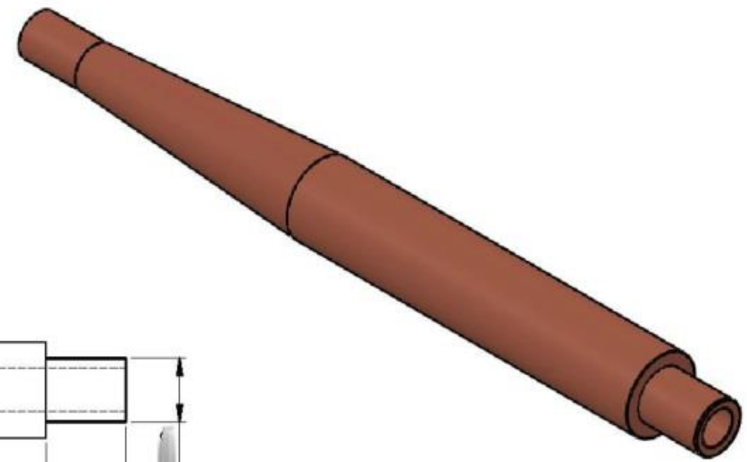
WIRE GUIDE CONICAL

Year	Week	Design checked by	Accepted for prod. by	Drawing checked by	Drawn by	Type	Scale	Code	Sheet	Rev.
2014	xx	.	.			.		20	1 (1)	x

V indicates R_a in µm .

-881	-880	Pos no.	Designation	Article number	Material Quality	Notation
			Wire guide conical		SS 5011-04	L=





Vikt:

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Alteration No.	Alteration	sign., year, month entered

Tolerances for untoleranced dimensions acc. to ISO 2768-1

Painting No. .

Compare No. .

SolidWorks

Release date: 2007-xx-xx

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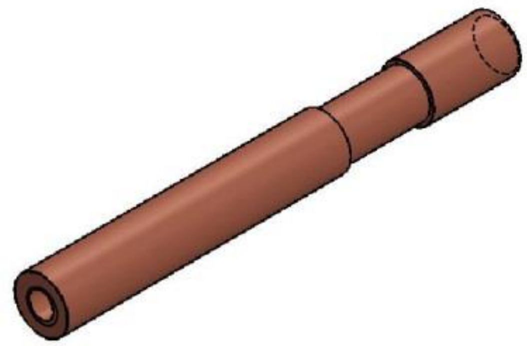
ESAB WELDING EQUIPMENT AB

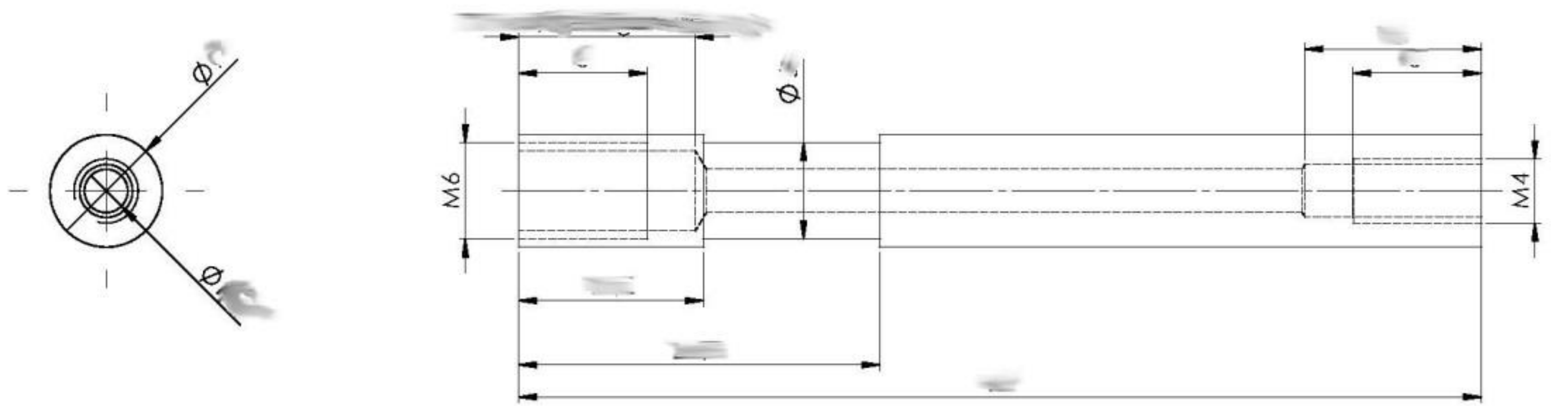
WIRE GUIDE STRAIGHT

Year	Week	Design checked by	Accepted for prod. by	Drawing checked by	Drawn by	Type	Scale	Code	Sheet	Rev.
2014		XX	.			.		20	1 (1)	X

V indicates R_a in µm .

-881	-880	Pos no.	Designation	Article number	Material Quality	Notation
			Wire guide straight		SS 5170-04	L=





Vikt:

Alteration No.	Alteration	sign., year, month entered
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Tolerances for untoleranced dimensions acc. to ISO 2768-1

Painting No. .

Compare No. .

SolidWorks

Release date: 2007-xx-xx

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ESAB WELDING EQUIPMENT AB

ESAB®

WIRE CONNECTOR

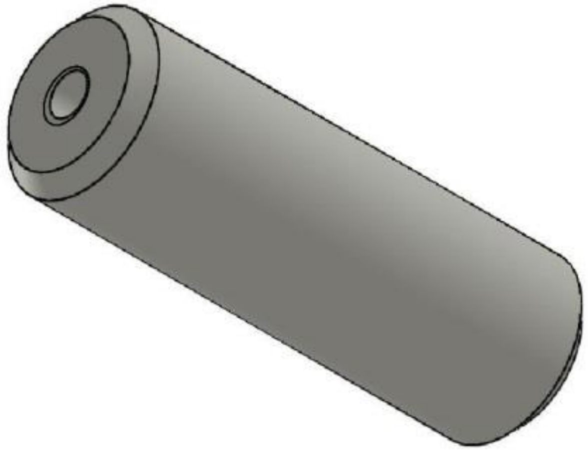
Type .

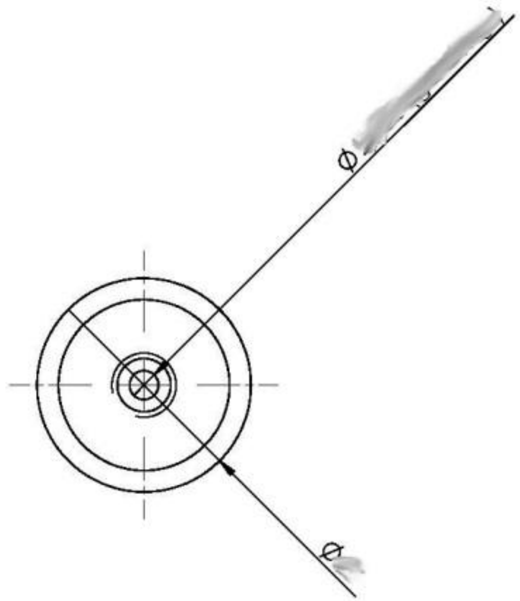
Scale	Code 20
Sheet 1 (1)	Rev. x

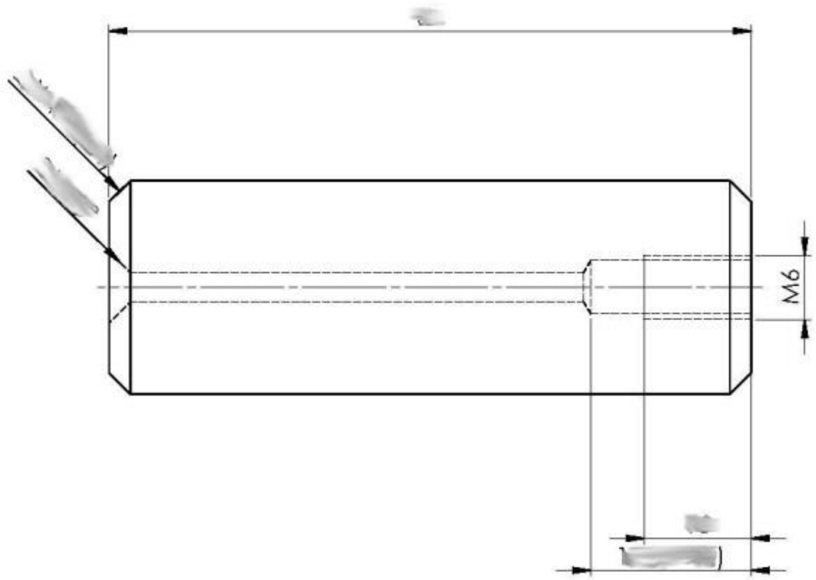
Year	Week	Design checked by	Accepted for prod. by	Drawing checked by	Drawn by
2014	xx	.	.		

V indicates R_a in µm .

-881	-880	Pos no.	Designation	Article number	Material Quality	Notation
			Wire connector		Stål	Stång, D=







Vikt:

Alteration No.	Alteration	sign., year, month entered
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Tolerances for untoleranced dimensions acc. to ISO 2768-1

Painting No. .

Compare No. .

SolidWorks

Release date: 2007-xx-xx

Denna handling får ej utan vårt medgivande kopieras, delgivas annan eller eljest obehörigen användas. Överträdelse beivras med stöd av gällande lag.

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ESAB WELDING EQUIPMENT AB

ESAB®

MOUNTING PLATE FEEDER

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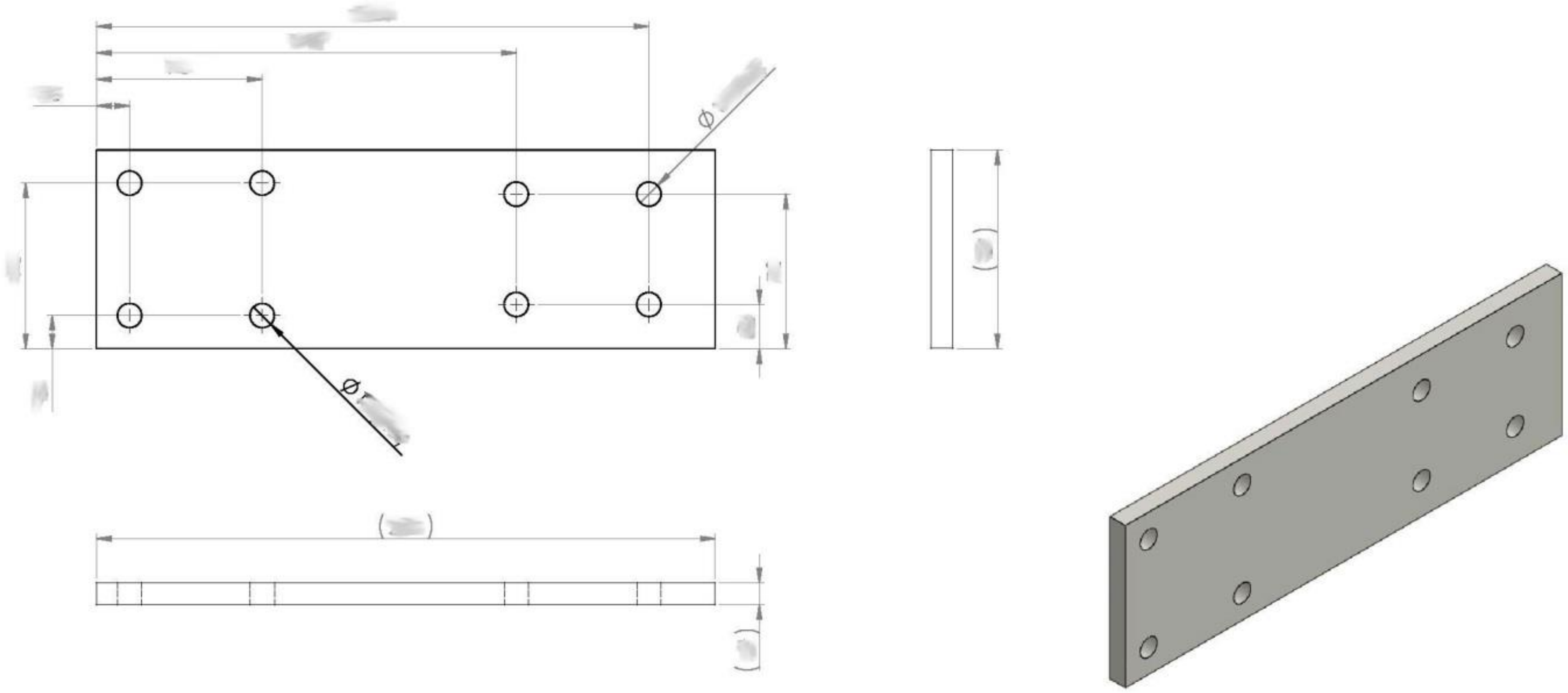
Type .

Scale	Code 20
	Sheet 1 (1)
	Rev. x

Year	Week	Design checked by	Accepted for prod. by	Drawing checked by	Drawn by
2014	xx	.	.		

V indicates R_a in µm .

-881	-880	Pos no.	Designation	Article number	Material Quality	Notation
			Mounting Plate feeder		S235JR	Plåt: T=



Vikt:

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Alteration No.	Alteration	sign., year, month entered

Tolerances for untoleranced dimensions acc. to ISO 2768-1

Painting No. 205

Compare No. .

SolidWorks

Release date: 2007-xx-xx

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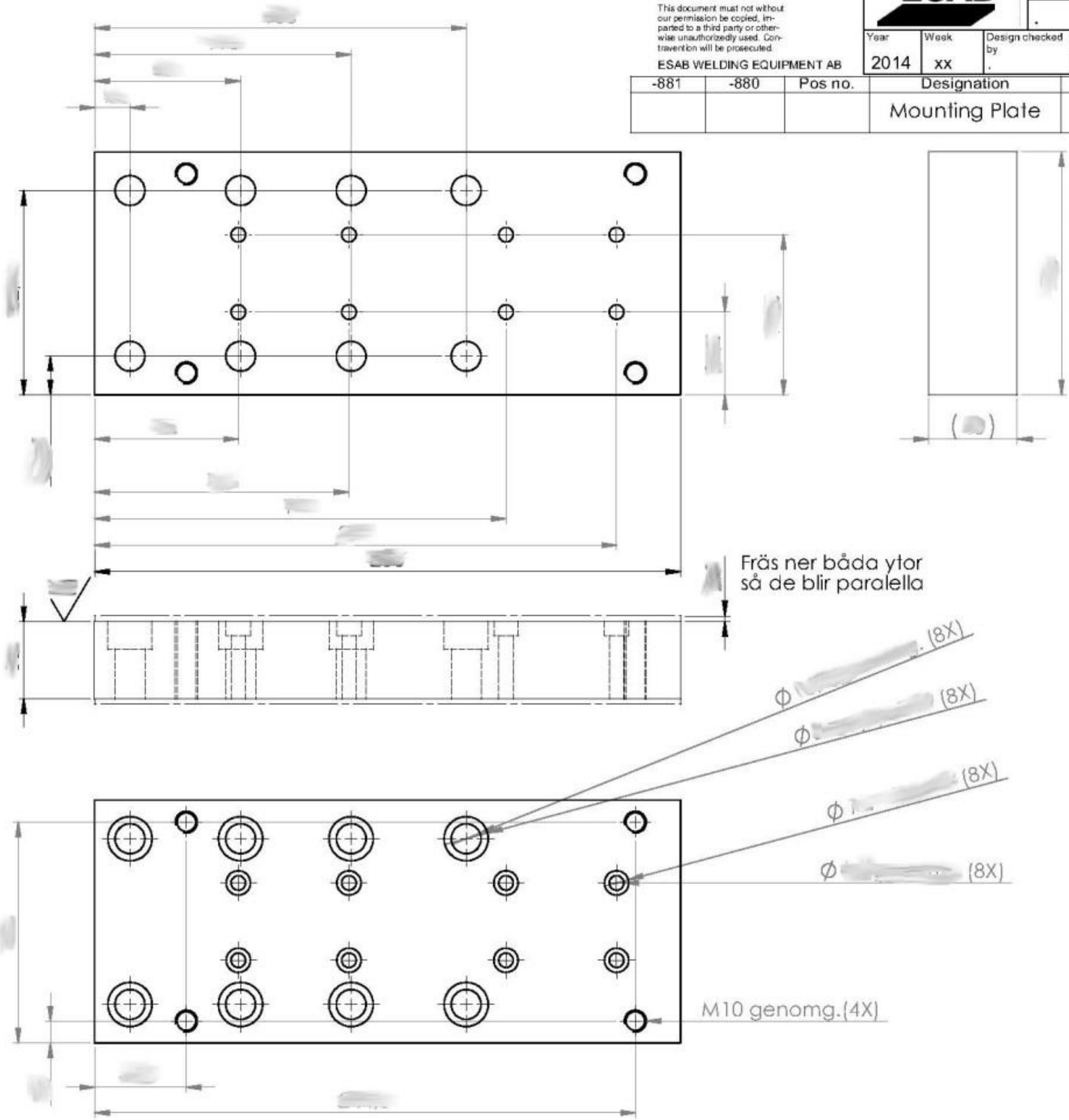
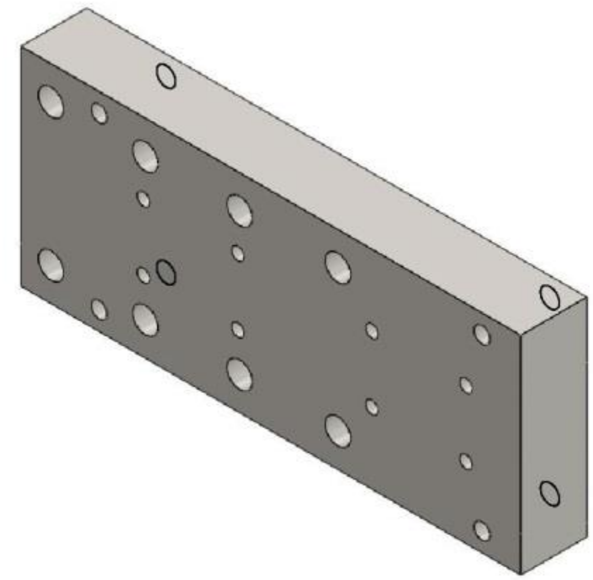
ESAB WELDING EQUIPMENT AB

ESAB®	MOUNTING PLATE					
	.					
	.			Type .	Scale	Code 20
Year 2014	Week xx	Design checked by .	Accepted for prod. by .	Drawing checked by	Drawn by	V indicates R_a in µm .	Sheet 1 (1) Rev. x

-881	-880	Pos no.	Designation	Article number	Material Quality	Notation
			Mounting Plate		S355J2	Plåt, T=





Vikt:

Alteration No.	Alteration	sign., year, month entered
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Tolerances for untoleranced dimensions acc. to ISO 2768-1	Painting No. 205
	Compare No. .

SolidWorks

Release date: 2007-xx-xx

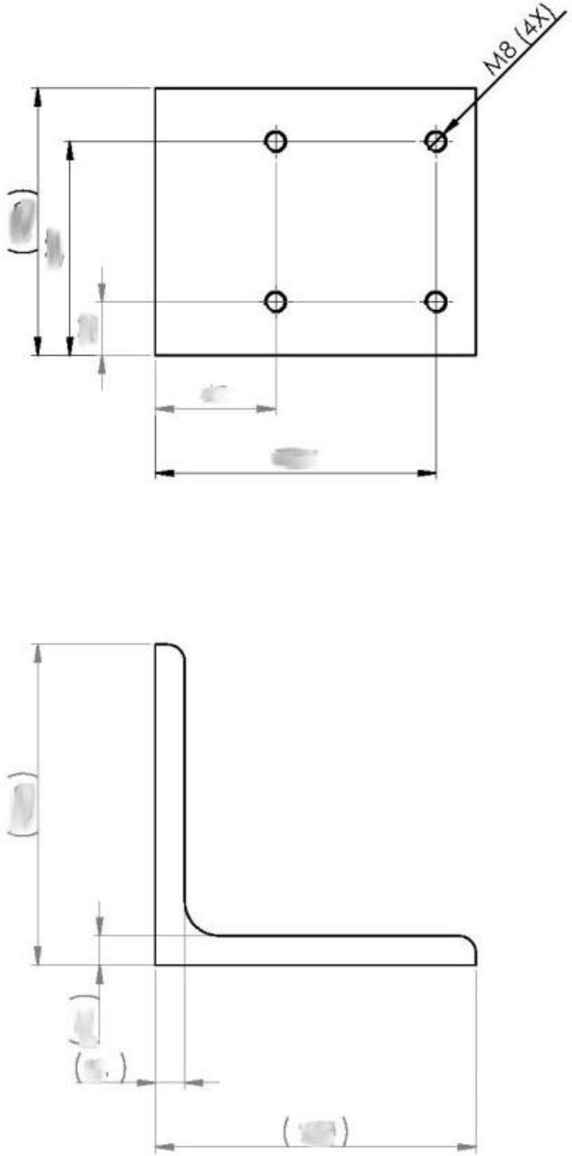
ESAB WELDING EQUIPMENT AB

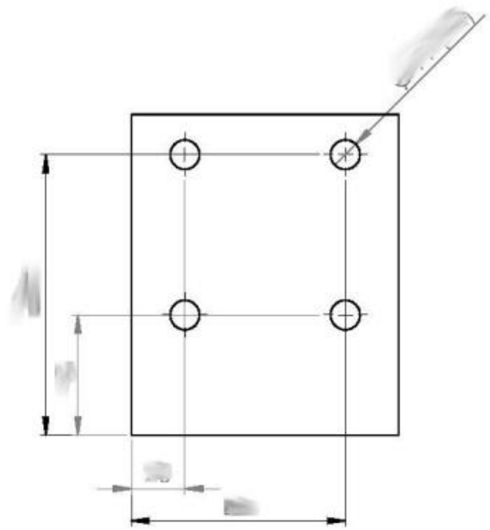
L-PROFILE

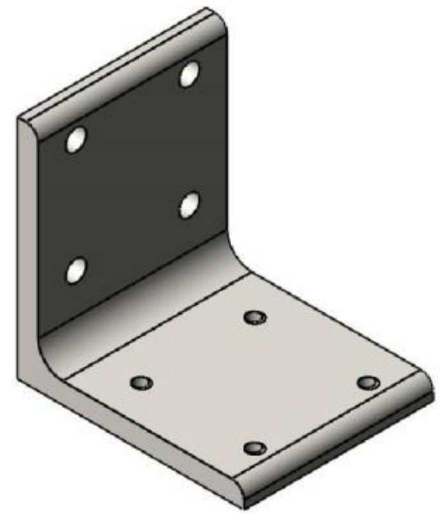
Year	Week	Design checked by	Accepted for prod. by	Drawing checked by	Drawn by	Type	Scale	Code	Sheet	Rev.
2014	xx	.	.			.		20	1 (1)	x

V indicates R_a in µm .

-881	-880	Pos no.	Designation	Article number	Material Quality	Notation
			L-Profile		Stål	L balk, , L=







Vikt:

Tolerances for untoleranced dimensions acc. to ISO 2768-1

Painting No. 205

Compare No. .

Alteration No.	Alteration	sign., year, month entered
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ESAB WELDING EQUIPMENT AB

ESAB

PINCHER

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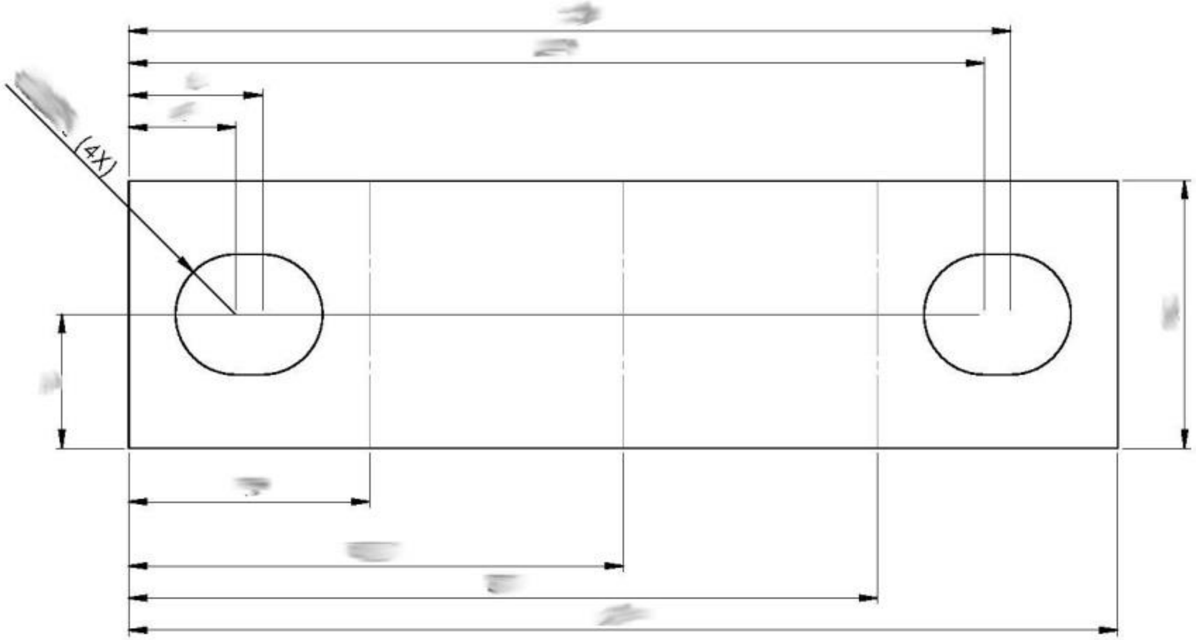
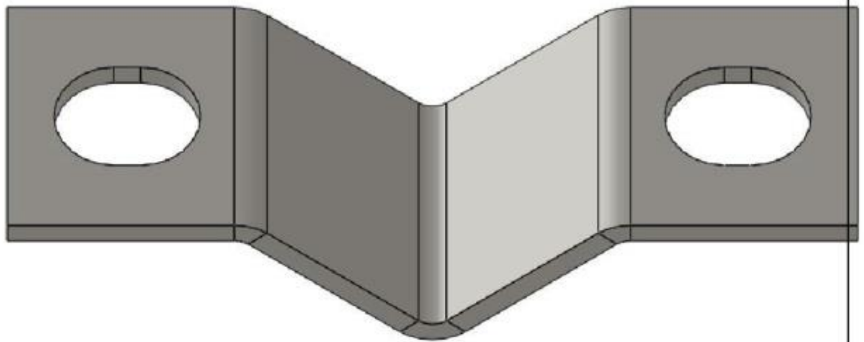
Type .

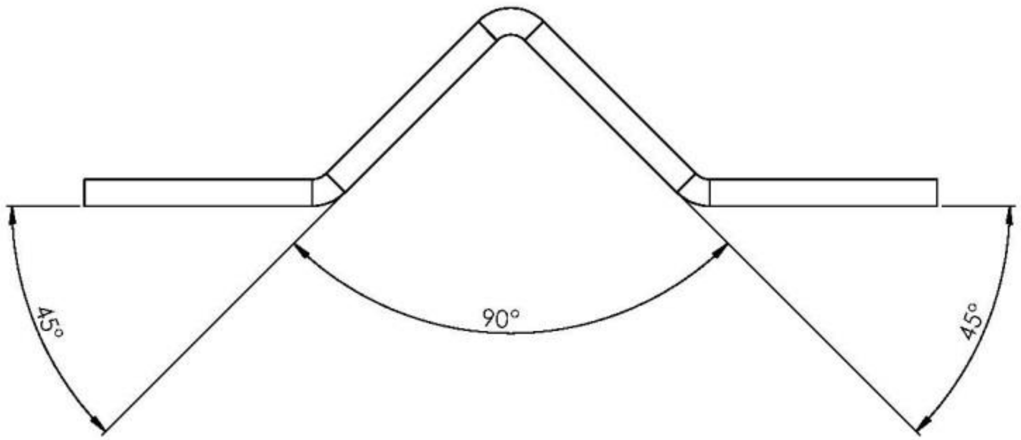
Scale	Code 20
	Sheet 1 (1)
	Rev. x

Year	Week	Design checked by	Accepted for prod. by	Drawing checked by	Drawn by		V indicates R_a in µm
2014	xx	.	.				.

-881	-880	Pos no.	Designation	Article number	Material Quality	Notation
			Pincher		Stål	Plåt,T=







Vikt:

Alteration No.	Alteration	sign., year, month entered
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Tolerances for untoleranced dimensions acc. to ISO 2768-1

Painting No. 205

Compare No. .

D2- Drawings for part 2

This chapter contains all production drawings for the developed parts for part 2. No assembly drawing has been included for part 2. This because no regulator has been mounted as stated in section 11.2 and therefore the assembly drawing would almost look identical.

SolidWorks

Release date: 2007-xx-xx

ESAB WELDING EQUIPMENT AB

ESAB ®

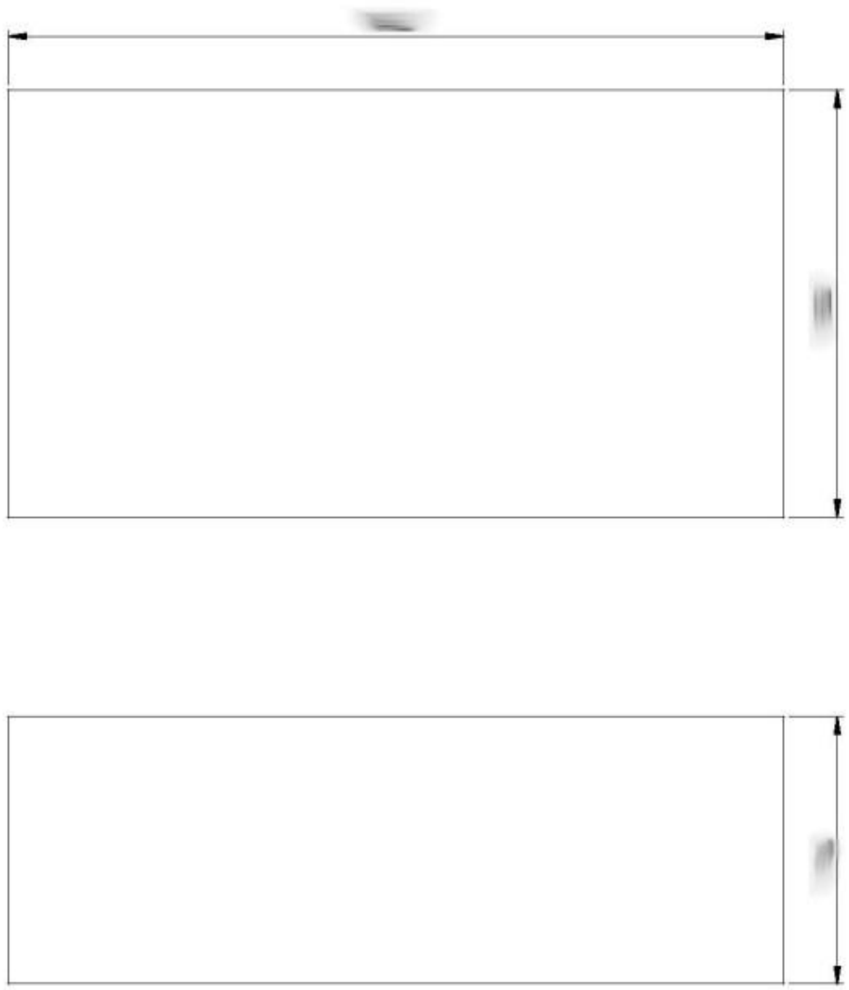
SHOULDER-HOLDER2

Skärritning

Year	Week	Design checked by	Accepted for prod. by	Drawing checked by	Drawn by	Type	Scale	Code	Sheet	Rev.
2014	xx	.	.			.		20	2 (2)	x

V indicates R_a in µm .

-881	-880	Pos no.	Designation	Article number	Material Quality	Notation
			Shoulder-Holder2			Plåt, T=



Alteration No.	Alteration	sign., year, month entered
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Tolerances for untoleranced dimensions acc. to ISO 2768-1

Painting No. .

Compare No. .

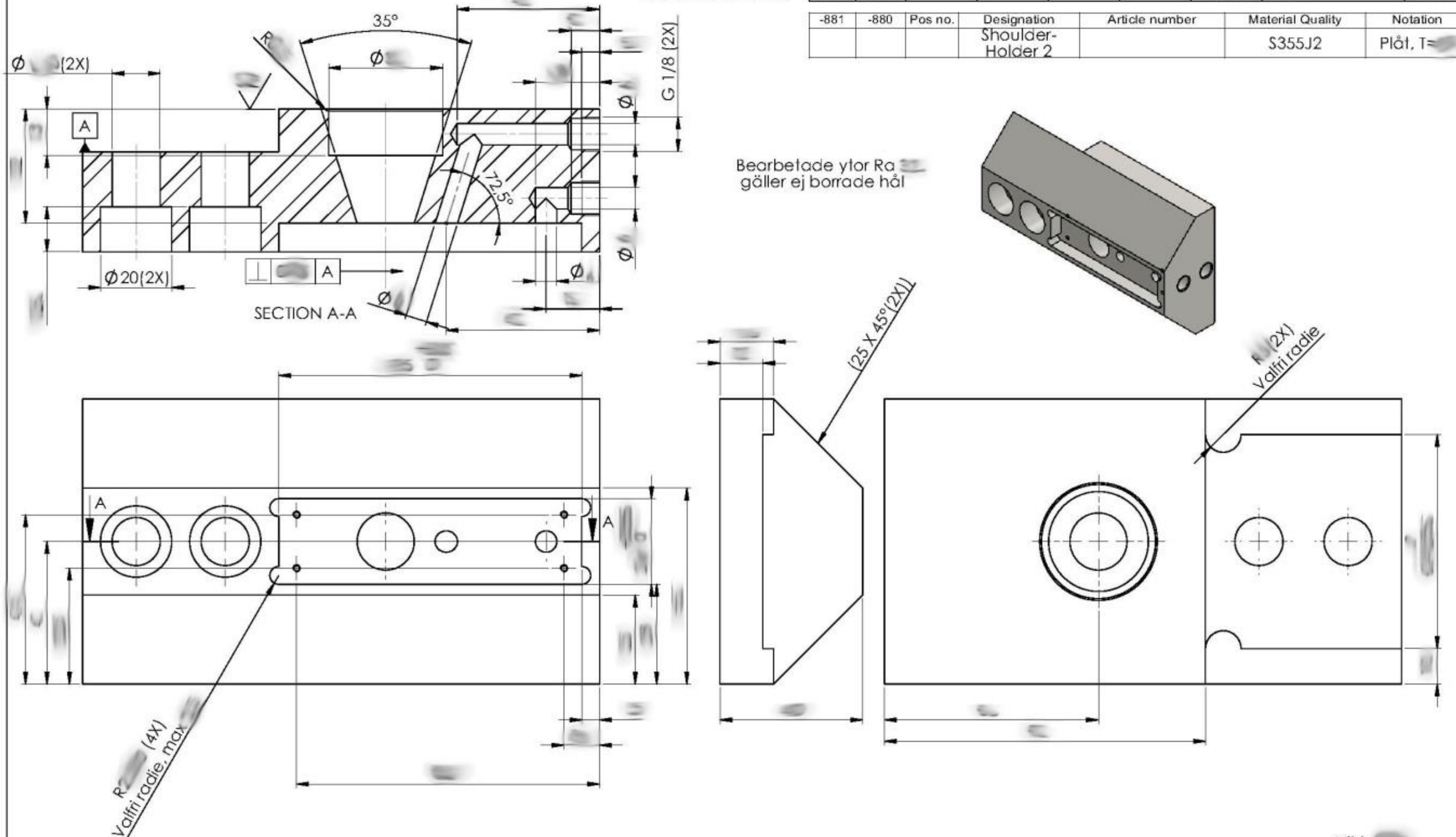
SolidWorks

Release date: 2007-xx-xx

ESAB

SHOULDER-HOLDER2								
Bearbetningsritning								
.					Type .		Scale	Code 20
Year	Week	Design checked by	Accepted for prod. by	Drawing checked by	Drawn by		V indicates R_a in µm .	Sheet 1 (2)
2014	xx	.	.					Rev. x

-881	-880	Pos no.	Designation	Article number	Material Quality	Notation
			Shoulder-Holder 2		S355J2	Plåt, T=



Vikt:

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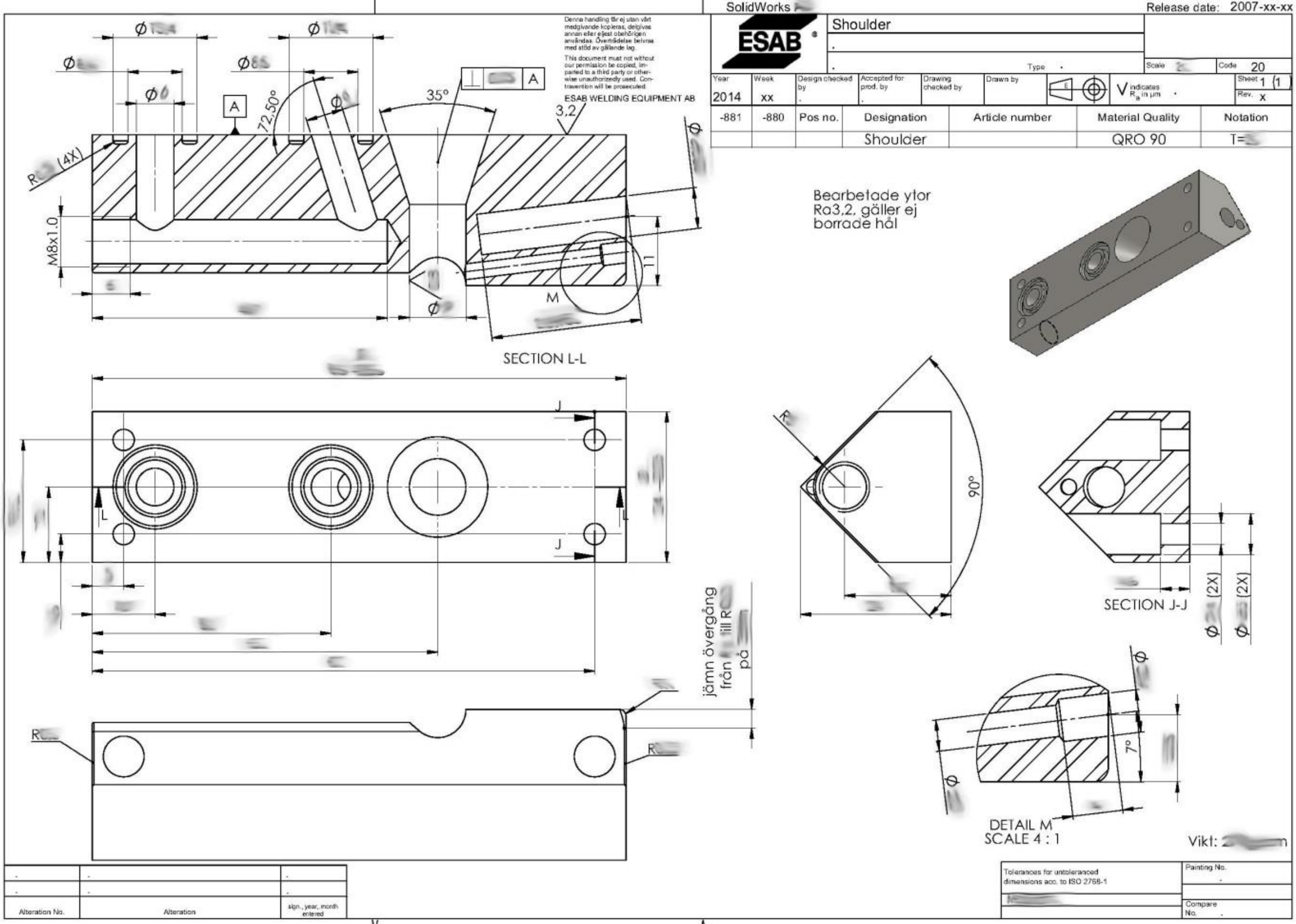
Alteration No.	Alteration	sign., year, month entered

Tolerances for untoleranced dimensions acc. to ISO 2768-1	Painting No. .
	Compare No. .



SolidWorks
Release date: 2007-xx-xx
ESAB
Shoulder
Type
Scale
Code 20
Sheet 1 (1)
Rev. x
Year 2014
Week xx
Design checked by
Accepted for prod. by
Drawing checked by
Drawn by
V indicates R_a in µm
-881
-880
Pos no.
Designation
Article number
Material Quality
Notation
Shoulder
QRO 90
T=
Denna handling får ej utan vårt medgivande kopieras, delgivas annan eller eljest obehörigen användas. Överträdelse beivras med stöd av gällande lag.
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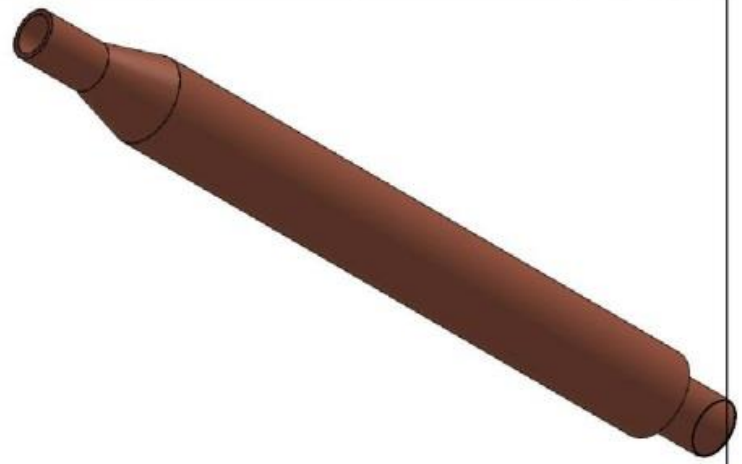
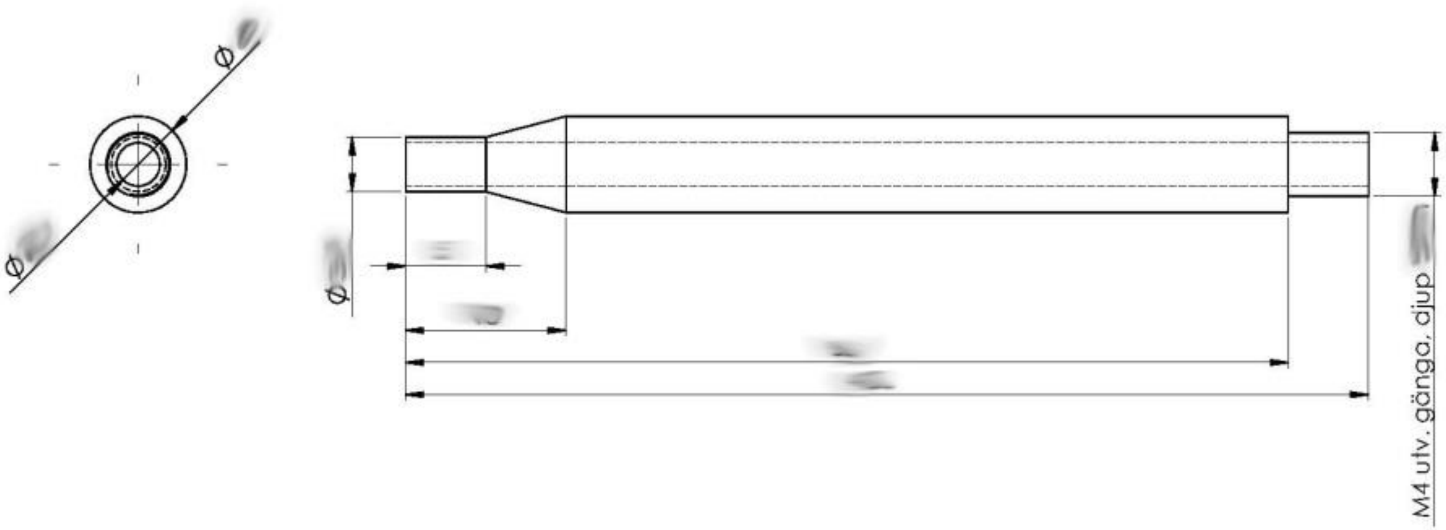
ESAB WELDING EQUIPMENT AB
M8x1.0
(4X)
72,50°
35°
A
3,2
11
M
SECTION L-L
J
L
Bearbetade ytor
Ra3,2, gäller ej
borrade hål
90°
SECTION J-J
(2X)
(2X)
jämn övergång
från till R
på
7°
DETAIL M
SCALE 4 : 1
Vikt:
Tolerances for untoleranced dimensions acc. to ISO 2768-1
Painting No.
Compare No.
Alteration No.
Alteration
sign., year, month entered

SolidWorks

Release date: 2007-xx-xx

ESAB®					Type .		Scale	Code 20
Year	Week	Design checked by	Accepted for prod. by	Drawing checked by	Drawn by		V indicates R_a in µm .	Sheet 1 (1)
2014	xx	.	.					Rev. x
-881	-880	Pos no.	Designation		Article number		Material Quality	Notation
			Wire guide conical				SS 5011-040	





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Alteration No.	Alteration	sign., year, month entered

Tolerances for untoleranced dimensions acc. to ISO 2768-1	Painting No. .
	Compare No. .

SolidWorks

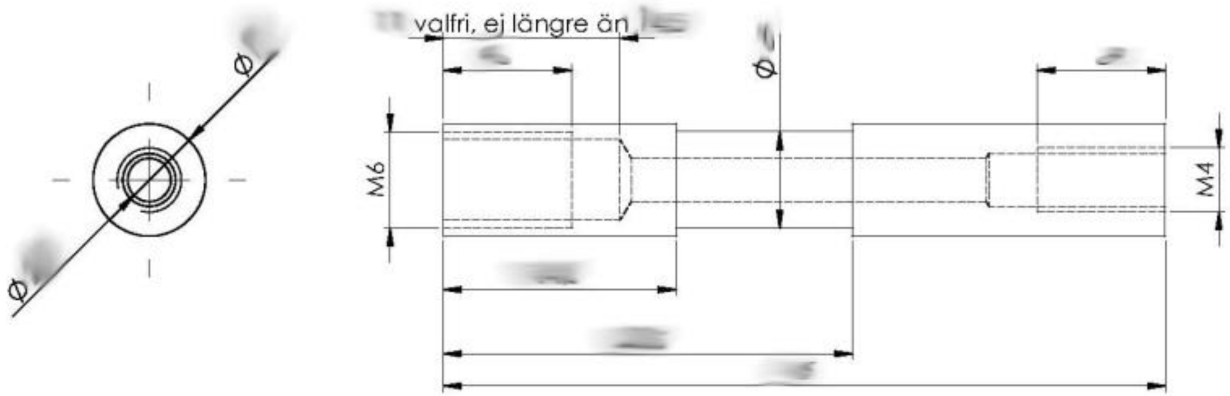
Release date: 2007-xx-xx

ESAB ®

WIRE GUIDE STRAIGHT

Year 2014	Week xx	Design checked by .	Accepted for prod. by .	Drawing checked by	Drawn by	Type .	Scale / Code 20 / Sheet 1 (1) / Rev. x
-881	-880	Pos no.	Designation	Article number	Material Quality	Notation	
			Wire guide straight		SS 5170-04		

V indicates R_a in µm .



Vikt:

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Alteration No.	Alteration	sign., year, month entered

Tolerances for untoleranced dimensions acc. to ISO 2768-1	Painting No. .
	Compare No. .