Teige, Audun Andre Solberg

WELDSIM Simulations of Alu-Steel Butt Welds Produced Using the Hybrid Metal Extrusion and Bonding (HYB) Process

Master's thesis

NTNU
Norwegian University of
Science and Technology

Preface

This master thesis is written during the spring of 2020 at the Norwegian University of Science and Technology (NTNU) meeting the requirements for a Master of Science, MSc, in Mechanical Engineering. The thesis is made under the Faculty of Engineering, Department of Mechanical and Industrial Engineering (MTP). With specialisation in Product Development and Materials Engineering. Supervisor of this project is Professor Filippo Berto with co-supervisor Professor Øystein Grong, inventor of the HYB process.

Acknowledgement

Abstract

Hybrid metal extrusion and bonding (HYB) is a solid-state joining method. Initially developed for joining of aluminium. But also capable of joining of dissimilar metals. The process uses filler wire and conform extrusion together with "stirring" from a rotating tool to form bonding under high pressure. This report is on welding simulation of an Al-Fe butt weld produces using the third generation of Al-Fe HYB welding. The simulations are done using the weld simulation program WELDSIM.

Results from simulations show great promise, realistic heat patterns with microstructural changes imbedded in the simulation. Temperature from the simulation has peak values over melting point. However, these are local and drop quickly after the heat source has passed. Therefore, the influence on the results are not significant. Hardness data show similar traits with test data available for this weld. Indicating an inclined HAZ after welding. WELDSIM is a great program for weld simulations. However, some new features are needed before the simulations can be perfect. This is currently being worked on by the creators of the program.

Sammendrag

Hybrid metal extrusion and bonding (HYB), er en fast fase sammenføynings prosess. Først utviklet for sveising av aluminium. Men også kapabel til å sveise ulike metaller. Prosessen bruker tilføring av materiale ved hjelp av conform ekstrudering sammen med "røring" av et roterende verktøy for å lage sammenføyningen under høgt trykk. Denne rapporten omhandler sveise simuleringer av Al-Fe buttsveis produsert ved bruk av tredje generasjons Al-Fe HYB sveis. Simuleringene er lagd ved hjelp sveise simulerings programmet WELDSIM.

Resultater fra simuleringene viser bra potensiale, realistiske varme mønster med endringer i mikrostrukturen innebygd i simuleringene. Temperaturen fra simuleringene har en topp som er over smeltepunktet. Men disse er lokale og synker raskt etter at varmekilden har gått forbi. Derfor, vil påvirkningen av resultatene ikke være signifikante. Hardheten viser lignende egenskaper som test data som er tilgjengelig på denne sveisen. Og indikerer en helling i den varmepåvirkede sonen. WELDSIM er et bra sveise simulerings program. Men noen nye egenskaper trengs før simuleringene kan bli perfekte. Dette er under arbeid av produsentene av programmet

Table of Contents

List of figures

List of equations

List of Abbreviations

AS	Advancing side
BM	Base material
CMT	Cold metal transfer
EZ	Extrusion zone
FE	Finite element
FEM	Finite element method
FM	Filament metal
FSW	Friction stir welding
GMAW	Gas metal arch welding
HAZ	Heat affected zone
HSLA	High-strength low-alloy
HYB	Hybrid metal extrusion and bonding
IMC	Intermetallic compound
RS	Retreating side
UTS	Ultimate tensile strength

1 Introduction

1.1 Motivation

Aluminium is a commonly used material in today's industry. Special material properties give the metal a large area of applications. Among other properties the high strength to weight ratio as well as good conductivity and corrosion resistance make the material highly sought after. The use of aluminium has been increasing more and more over the recent years (Figure 1). Many different factors help expand the aluminium production. New application areas in addition to significant increase in developed sectors makes the predictions expect a continuation of the curve [1]. Climate change is one of the largest fields of focus lately. And will be in the foreseeable future. Aluminium is one of the materials that have seen an increase in application areas from the pursuit for more environmentally friendly solutions. For example, the automotive sector has seen a rise in substitution of heavy parts with parts made from aluminium. To reduce emissions by reducing the weight of the vehicle. The amount of aluminium in new vehicles are expected to increase by 40% from 2016 to 2028 [2]. Even with this increase, aluminium will not replace steel as the most used material in cars. Therefore, a good method which enables bonding between the metals will be important.
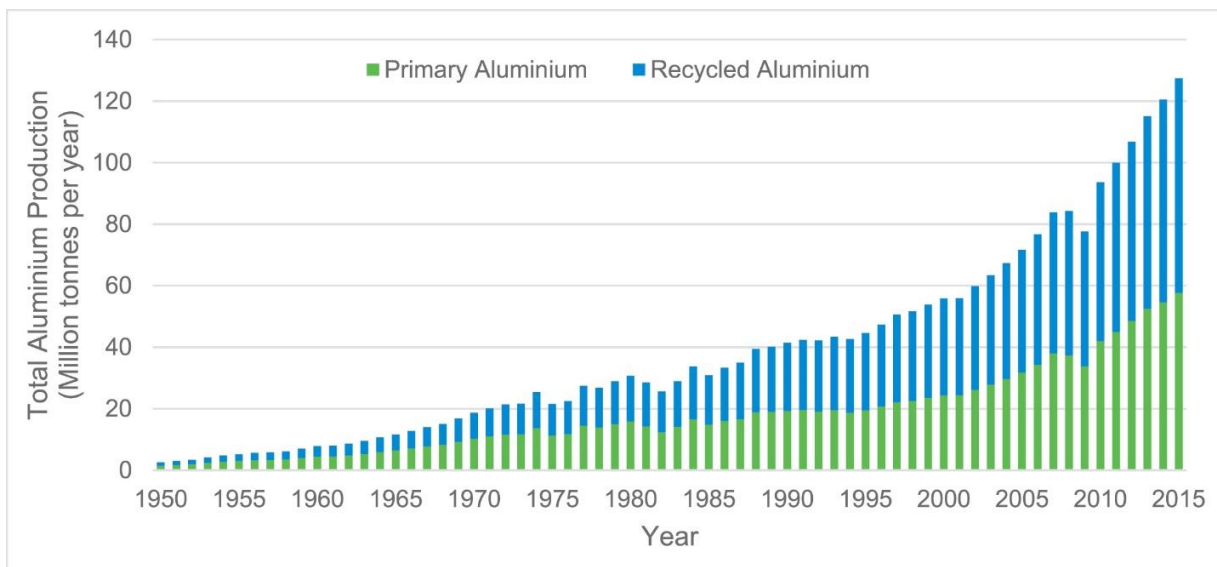
Figure 1 Illustration of increased aluminium production per year split into primary and recycled aluminium

Another motivation behind this thesis is to get to know the work behind an innovation like the HYB process and to work on a new and exciting topic. Using WELDSIM for simulations that have never been done before on HYB welds is intriguing.

1.2 Objective

This thesis a continuation from a project work from the fall of 2019 [3]. The project was on fracture behaviour of aluminium to steel joints, made using the HYB technology. The joint where analysed using a FE-model in Abaqus. Ductile fracture behaviour in a test specimen was possible to replicate in the simulations. With comparable angle, stress, and location on the fracture (Figure 2). A previous master thesis by Marie Mathiasson have analysed the fatigue fracture of HYB joints. Showing realistic results on large initial cracks [4]. However, more accurate data is needed to simulate fatigue fracture on smaller initial cracks. Like what is seen in the latest HYB joints.
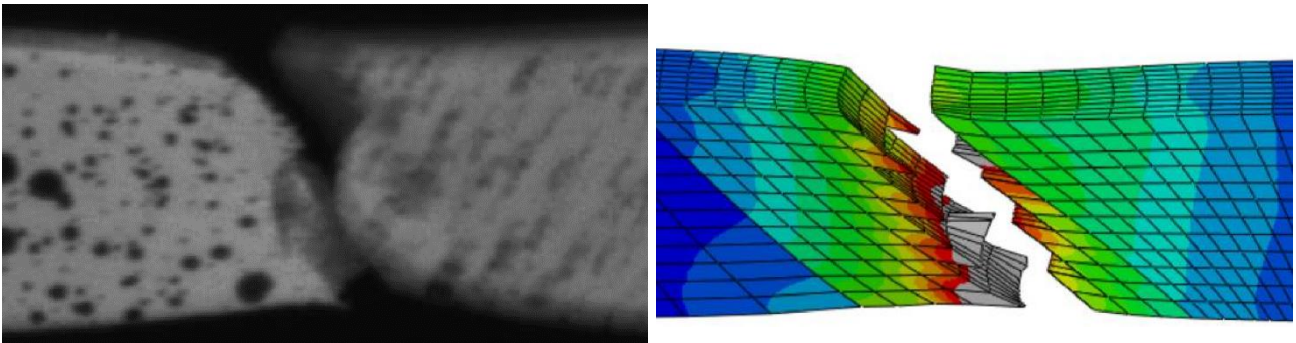
Figure 2 Fracture location and angle from the a) test specimen b) ABAQUS simulation [10]

The main objectives of this thesis are to take the simulations one step further by simulation of the welding process itself. And to investigate the possibility to accurately simulate HYB welding between aluminium and steel plates. To get the best possible results a complex weld simulation program called WELDSIM is being used. The program has no user interface and are therefore not widely used. However, it is one of the most advanced and complex welding simulation programs available. WELDSIM uses the thermal field and thermal history to account for the microstructural changes in the weld during simulation. This makes the mechanical calculations later in the process more accurate with realistic and updated material properties in the HAZ based on the changes in the material. Thereby, it gives a unique possibility to get accurate results on difficult simulations.

There are a lot of interesting strenuous metallurgical work put into the WELDSIM model. However, this thesis will focus mostly on the setup of the simulation and results. Because of its relevance to this thesis.

The goal of this thesis is to get a realistic simulation of the weld in order to get material properties in the different zones. For example, hardness, yield strength, in addition to residual stresses and distortions. Hopefully, the results will be useful in further work on the HYB process. Accurate residual stresses will be important for the further simulation and understanding of fatigue behaviour in aluminium to steel welds. Another element of this project is to investigate if a program like WELDSIM can be uses in this kind of simulations. WELDSIM shows great promise with many advanced options. There is very little aluminium to steel welding-simulations and none on the HYB process. These simulations might show areas where the program can be helpful. Or if WELDSIM simulations are feasible for further work within simulations on the HYB process.

2 Theory

2.1 Aluminium

Aluminium is known as a lightweight metal with good corrosion resistance, high thermal and electrical conductivity and excellent formability [5]. This gives aluminium a wide range of application areas. From small appliances in electrical products and consumer goods, to large constructions and cars. High specific strength for its price is probably the most significant attribute of the metal. Aluminium has seen an increased use in most industries. But especially in the transportation industry. In construction and electrical industries, the low weight of aluminium reduces the need of support structures and foundations. In addition, the great corrosion resistance gives a natural protection against nature and reduces maintenance. Not only the properties of aluminium give it increased production. Everyday devices like phones, laptops and design items use more and more aluminium, for visual effects and to make the product feel more exclusive.

Welding of aluminium is often difficult compared with steel. Changes the alloying elements make to the aluminium, often transform when subjected to heat. The HAZ in aluminium welding are therefore often weaker, softer, and more ductile than the base material. The high thermal conductivity of aluminium works against the material, spreading the heat deeper in the metal and creating a larger HAZ than it would have had if the thermal conductivity were lower, like in steel.

Aluminium is a low strength metal. But is easy to strengthen using alloying elements. Alloys are categorized in different series based on what main alloying elements there are in the different alloys. The different categories often have different properties and main application areas where they fit best in with regards to cost and desired properties. The aluminium used in this project is in the 6000-series

2.1.1 6000-series Aluminium

The main alloying elements in 6000-series aluminium is silicon, manganese, and magnesium. The series is known for its heat-treatability making it one of the most used alloys in welding fabrications. A lot of different phases can be observed in the microstructure depending on the cooling rate and alloying elements present [6]. The aluminium used here is 6082 aluminium alloy. High strength and good corrosion resistance make the alloy perfect for structural components.

2.2 Steel

Steel is the most used material today and is used in almost every industry. Steel can and is used all over because of the wide range of properties, great availability, and relative low cost. Alloying elements as well as treatment of the metal can give steel almost any wanted properties. Since steel is so commonly used it also means that it is available across the world, making it an easy metal to choose. Furthermore, large availability and usage mean that there are a lot of experience about the different steel types. Most steels are relatively easy to work with in regards of welding, formability, and machinability. Steel have such a wide range of properties that it can go from being a soft and ductile material to super hard and brittle. Steel can compete with aluminium in regards of specific strength. Even with almost three times the weight, but then the steel is often too brittle or too expensive compared with the aluminium.

2.2.1 HSLA Steel

High-strength low-alloy (HSLA) steel is a collective term for many different steels of low-carbon alloys. HSLA can contain alloying elements such as copper, vanadium, nickel, and molybdenum in combined concentrations as high as 10 wt%. Giving them a stronger resistance to corrosion than plain carbon steel. As well as high strength, ductility, and formability [7]. The steel used in this project is a HSLA steel.

2.3 Joining of aluminium and steel

Bonding of aluminium and steel is a challenging process. Large difference in mechanical and thermal properties make many welding processes inadequate. However, some methods have been successful in creating decent bonding between aluminium and steel, Friction stir welding (FSW), Cold metal transfer (CMT), Gas metal arch welding (GMAW) and Hybrid metal extrusion and bonding (HYB) [8-11]. A more thorough review of the differences between the welding methods and different generations of HYB welding, can be found in the project work done before this thesis [3].

Temperature is a key factor in creating strong bonding between steel and aluminium. The bond between the aluminium and steel is achieved thru intermetallic compounds (IMC). Since IMC are what bonds the aluminium and steel it cannot be avoided. However, large IMC are too brittle and weaken the weld and therefore a minimum amount is desirable. Tanaka et al. argued that IMC thickness is largely affects the bond strength across the interface between aluminium and steel for FSW [12]. The formation of brittle IMC in the interface increase greatly with increase of temperature [13]. Therefore, low temperature, solid-state bonding methods have a natural advantage against welding methods that rely on melting of material to achieve bonding.

Little heat absorbed in the aluminium is the one of the main requirements for a good aluminium weld [14]. Not only because of the brittle IMC in the interface. But also, because of the HAZ in aluminium, where the area impacted by the heat input form welding is typically 30-50 percent weaker than the unaffected material [15].

There is a large difference in solubility of hydrogen between liquid and solid aluminium (Figure 3)[16]. Gas porosity induced by hydrogen is another severe problem in fusion welding of aluminium. Excess hydrogen creates pores in the metal during solidification leading to reduced tensile and fatigue properties [14]. This also indicates that a solid-state bonding method like FSW or HYB have an advantage over welding processes reliant on melding of the aluminium.
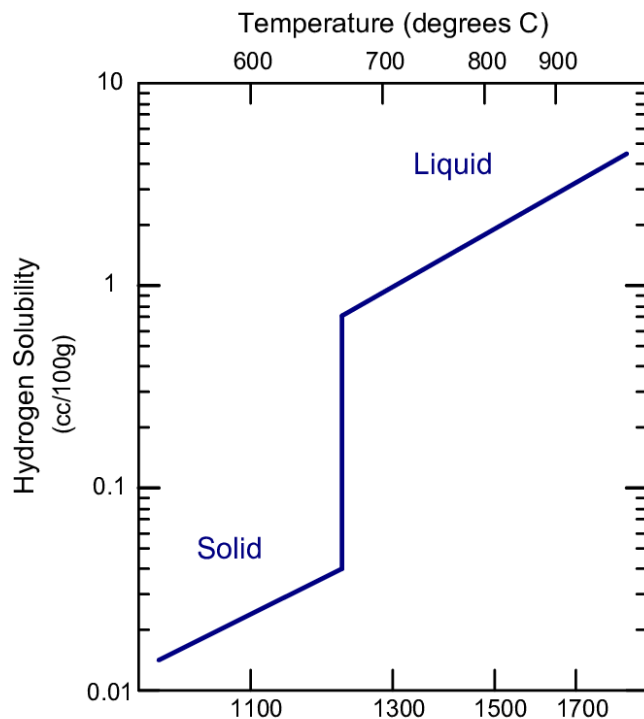
Figure 3 Solubility of hydrogen in solid and liquid aluminium [16]

2.4 Hybrid Metal Extrusion and Bonding (HYB)

Hybrid metal extrusion and bonding (HYB) is a bonding process that uses filler material and conform extrusion [17], to form bonding. Filler wire is extruded thru a rotating pin and deposited on the base material. HYB is a method that uses some the best parts from the other welding processes. Using a filler wire like CMT and GMAW and still being a solid-state welding method like FSW. Making it possible to maintain a high welding speed. As previously mentioned, the process was at first intended to preform Al-Al butt welds. Which it has done with good results [18]. But it has been developed further and is now able to create bonding between dissimilar materials.

Welding using the HYB process is in constant development. The process that is being used here is the third generation Al-Fe HYB weld, the latest version. The third generation HYB weld is using a circular pin. Bonding is achieved thru intermetallic bonding in the Al-Fe interface and metallic bonding between Al-BM and Al-FM.

Figure 4 shows a cross-section of how the plates and tool are setup in the process. The aluminium and steel plates are placed on a working bench, with a 3mm gap between them. A rotating pin with a diameter of 7mm stir some of the aluminium base material (BM) while extruding filler wire to fill the void between the plates. There is no machining done by the tool on the steel plate, as the tool only lays close to and moves along the edge of the steel.
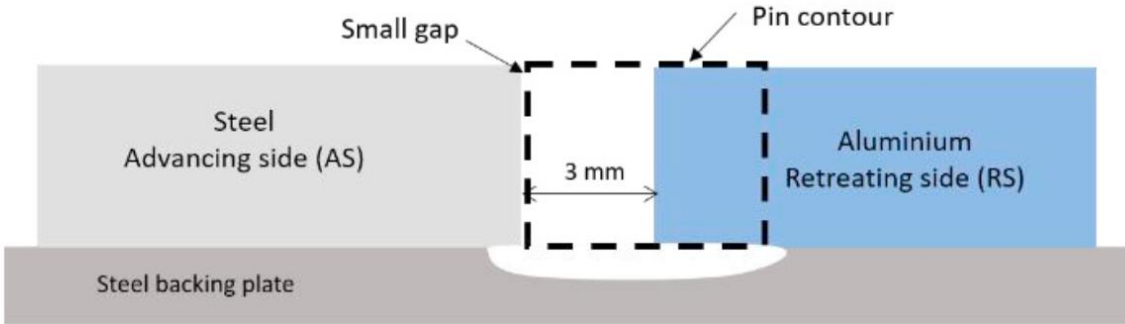
Figure 4 Visualization of pin and plate placement a in third generation HYB-welds [8]

After welding the different zones can be seen in Figure 5. A good mixture of Al-BM and FM can be seen in the extrusion zone (EZ). And close to no machining done to the steel side of the weld.
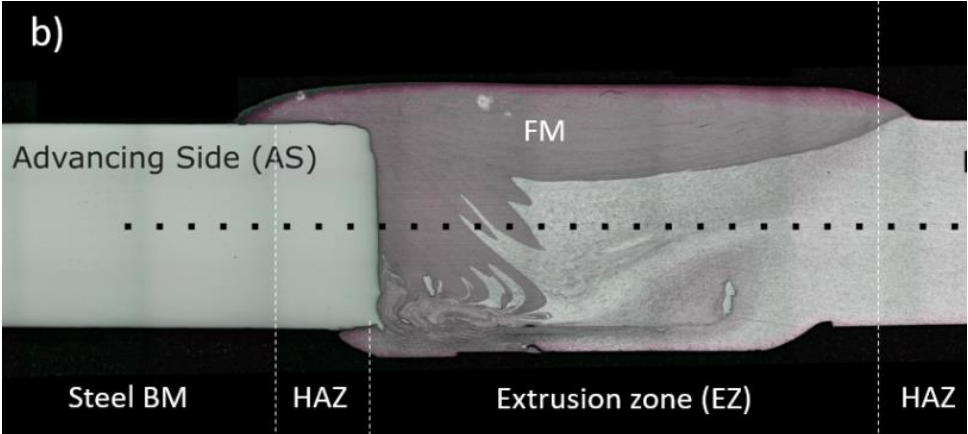
Figure 5 Cross-section of the weld after welding split into different zones
(Sandnes , L. Personal communication 2019)

2.5 WELDSIM

WELDSIM is an advanced program used for simulating welds. The simulations are versatile and very adaptable. From Figure 6 the main inputs and outputs from WELDSIM is illustrated. Showing that every aspect of the weld can be chosen and changed to make the simulation as realistic as possible. Outputs from the simulation are not only the normal outputs like stresses and distortions. But also include the evolution of the temperature, making it possible to predict the changes in strength and microstructure.
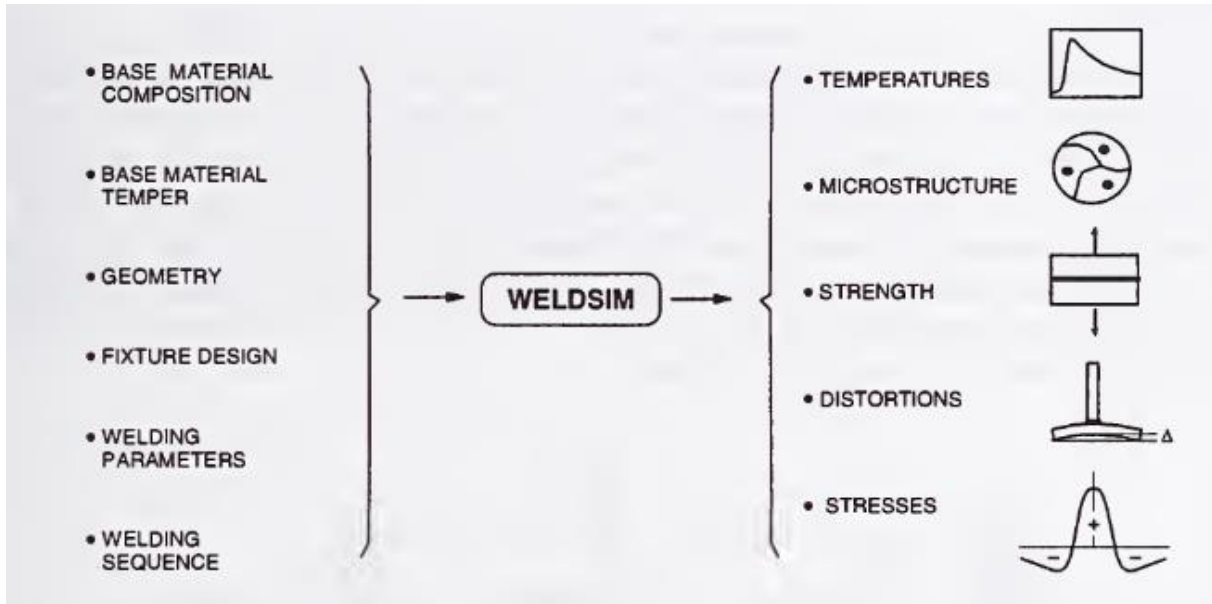
Figure 6 Illustration of the main input and output from WELDSIM stresses [19]

The model is capable to reproduce real life welding results quite accurately by combining multiple models. A thermal model, mechanical model, and a microstructural model works together to give realistic reproduction of the weld, increasing the accuracy of the simulation. The thermal model influences both the microstructural changes in the material as well as the stresses and deformations in the mechanical model (Figure 7). The microstructural changes also influence the mechanical model by changing the mechanical properties of the materials. This is what gives WELDSIM its high accuracy. The simulation tool have been used in different situations and have adequately predicted deformations, heat flow and residual stresses [19].
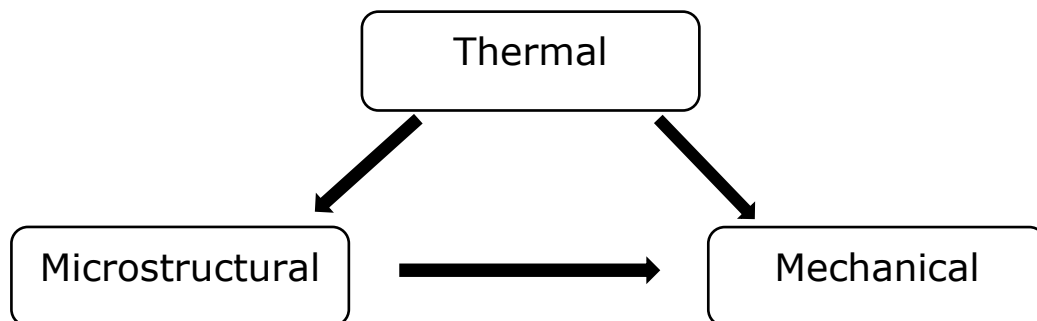
Figure 7 Illustration of the influence between sub-models in WELDSIM [19]

Thermal model: Finite element method (FEM), principles of energy conservation together with thermal boundary conditions and thermal properties. Is used to solve the thermal model in WELDSIM. The thermal properties must be set for the specific materials in the simulation and for all interfaces. Being able to control the specific heat transfer coefficient on all interfaces in addition to having full control over the heat input gives us good control over the thermal field.

Heat input in WELDSIM is based on the double ellipsoidal geometry principles presented by Goldak *et al*. This gives an increased possibility to modify the heat input and show both the shallow and deep heat transfer in conventional welding [20]. This theory was introduced to help simulate arc welding. However, the added flexibility of the heat input is also essential in simulating welds produced using the HYB process. In addition to the double ellipsoidal heat input there is a gaussian surface heat source to account for the friction heat produced by the top of the tool during welding. There is a friction stir heat source option built in the WELDSIM program. However, the model is simplified and assumes that the pin forces a given temperature inside a circle of the material under the pin [21]. This assumption, and the fact that HYB also adds material during the process makes the friction stir heat option unfit for this simulation.

Microstructural model: In WELDSIM the evolution in the microstructure during and after welding is accounted for in a particle size distribution (PSD) model. The theory behind the microstructural model is well documented in these articles [22-26] and described in the WELDSIM reference manual [21]. The implementation of the complex microstructure simulation is one of the best features in WELDSIM and what makes it different than most other weld simulation programs. PSD model can be split into three components. Firstly, the nucleation law that describes the rate of precipitation in the material. The second component is rate law of particle growth or dissolution. The material consists of different particle sizes, these are split up in different size classes and the rate law calculates the dissolution or growth rate of each particle size class. Lastly a particle flux model is used to correctly distribute the particles after the growth or dissolution of the particles.

Mechanical model: The mechanical model is solved with FEM, using the same mesh and elements as the thermal model. The model is built quite similarly to most mechanical simulation models. Using numerical calculations for each point in the mesh to replicate real life strains and stresses. However, with the microstructural changes simulated by the previous steps the material properties in the mechanical model are more like a field. Consisting of many small changes in material properties depending on the thermal history and particle growth and dissolution. Making the mechanical model more like materials seen in real life, not having to make clear lines dividing the material in different zones and assigning material properties thereafter.

3 Welding Simulation of Al-Fe HYB Weld

The objective behind doing a simulation of the HYB weld is to get a better understanding of how the weld will behave in different situations. And to get a better overview of how the weld is today. For example, by getting a more accurate temperature history and HAZ by using the microstructural evolution implemented in WELDSIM. In the case of fatigue strength, the residual stresses will have a large influence and are therefore important to identify.

3.1 Pre-Prosessing in Patran

To be able to use WELDSIM as a simulation tool we need some support from other programs, to make the input files needed. Since WELDSIM does not have any user interface or way to make geometries, Patran where used for that in this project. Other similar programs can be used. Patran is the world's most widely used pre/post-processing software for Finite Element Analysis (FEA) [27]. And was available at NTNU. It can be used to make geometries, desired mesh, and simulation setup. In addition to post processing and post analysis of finished simulations. Here Patran was used to make geometries, mesh, and tags that make it possible to distinguish between different bodies and interfaces. The finished Patran file was exported as a neutral text file for WELDSIM to be able to read it.

3.1.1 Geometry

The welded geometry consists of five different sections, as can be seen in Figure 8 and Table 1. Number one is the Al-BM, that is the part of the aluminium plate that does not come in contact with the welding tool. Then the part of the aluminium plate that is machined or stirred by the tool and mixed with the FM. The red area, number three, is the area that is a void before welding. And is filled by the addition of FM in the welding process. There are two steel sections. The first one is the steel plate that is being welded. This does not have to be sectioned in any more parts as the tool does not directly affect the steel. The last section of the geometry is the steel backing. This is included in the simulations to take into account the heat that is transferred to the backing in the welding process.

The geometry and sections have all been chosen to match the latest from HYB Al-Fe bonding. Where 4mm thick 100x500mm aluminium and steel plates were joined. The backing was chosen to be 100mm thick to be large enough to absorb the same heat as the backing does in the process, without increasing too much in temperature. The gap between the plates before welding is 3mm wide and will be filled by the
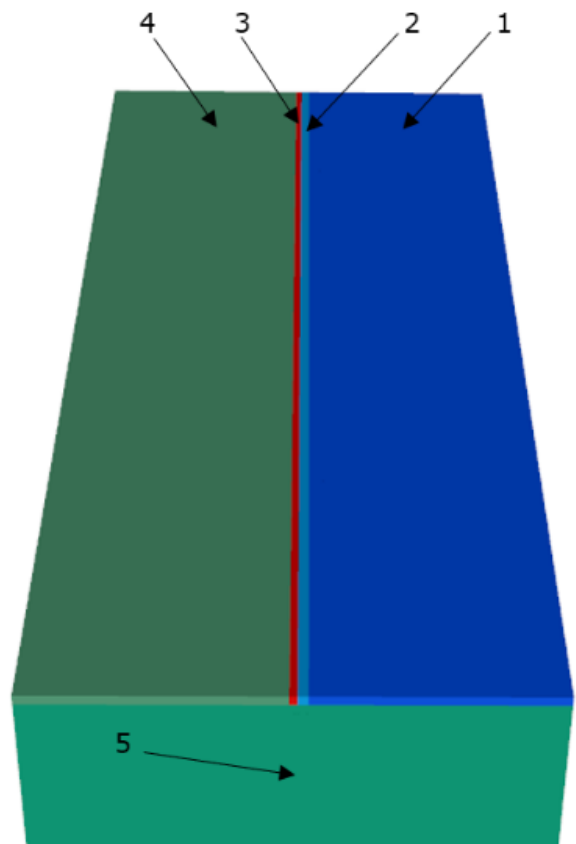
Figure 8 Sections of the welded geometry

filament material. Section 2 in the figure is 4mm wide to cover the rest of the area under the 7mm in diameter wide pin. Making it possible to add heat input to the whole area under the pin and not just the area that gets material added.

Number	Description	Material
1	Aluminium Base Material	Al 6082 - t6
2	Al-BM, stirred under welding	Al 6082 - t6
3	Gap between plates/ FM stirred under welding	Al 6082 - t4
4	Steel Base Material	HSLA – Steel
5	Steel backing plate	HSLA – Steel

Table 1 Sections of the weld with associated description and materials

3.1.2 Mesh

Meshing was also done in Patran. For this simulation, a linear hexahedral mesh was chosen because of the relatively easy geometry. The simplicity of the hexahedral elements makes them easier to use in WELDSIM compared with tetrahedral or triangular prisms. To reduce the calculation time needed the element size is decreased in areas of interest and increased in areas without great influence. Element size range from about 1.5mm to 10mm. In Figure 9 b) an overview of the whole mesh can be seen. It's clear to see that the mesh is not uniform and becomes smaller closer to the weld. In Figure 9 a) there are a more closeup view of the mesh around the welding zone. Small elements can be seen in the weld proximity. Used to get more precise results in the area of interest.
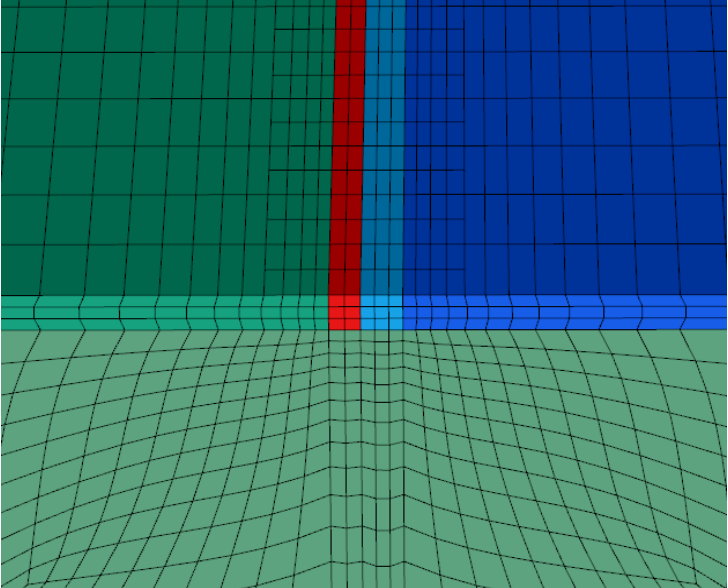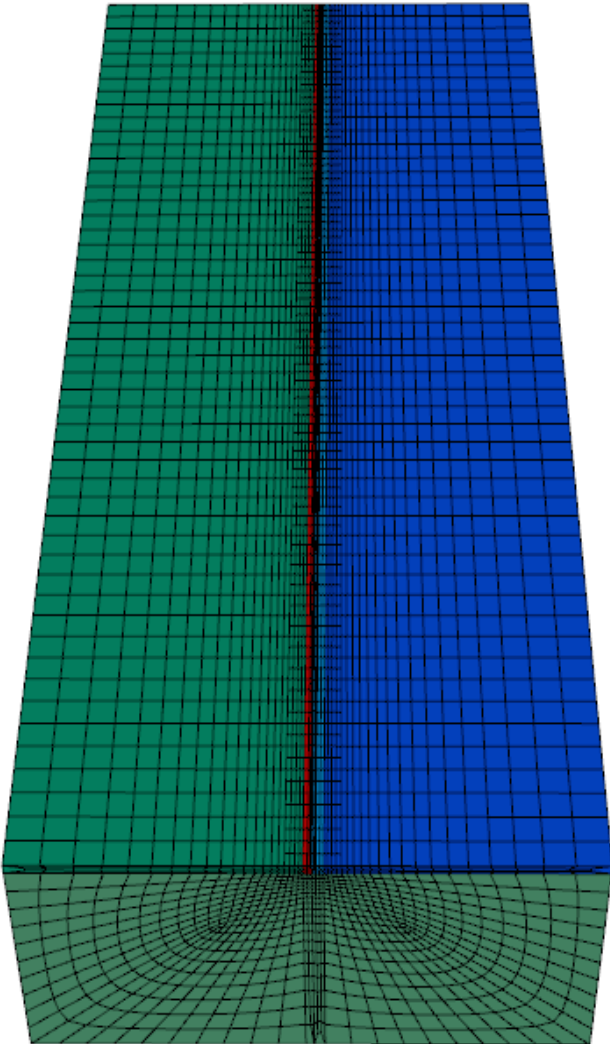
a)   b)

Figure 9 Illustration of the mesh made in Patran with, a) details around the weld. b) overview over the whole model

3.1.3 Identification Tags

For WELDSIM to be able to understand and use the pre-processing done in Patran there are a few tags that need to be included. These tags are how WELDSIM is capable to interpret the neutral file exported from Patran. And should not be mixed with real mechanical properties. The mechanical properties used in the simulations will later be determined in the WELDSIM code. A detailed description of how the identification tags where given can be found in appendix A

3.1.3.1 Geometric Tags

One material was made for each of the different sections of the geometry. Each material where then given a density from 1-5. Materials where assigned according to the numbers seen in Table 1. Matching the "density" to the number given in Table 1 and Figure 8 makes it easier when we import the geometry to WELDSIM. In the WELDSIM code the density becomes an ID for the section and does not have any physical meaning.
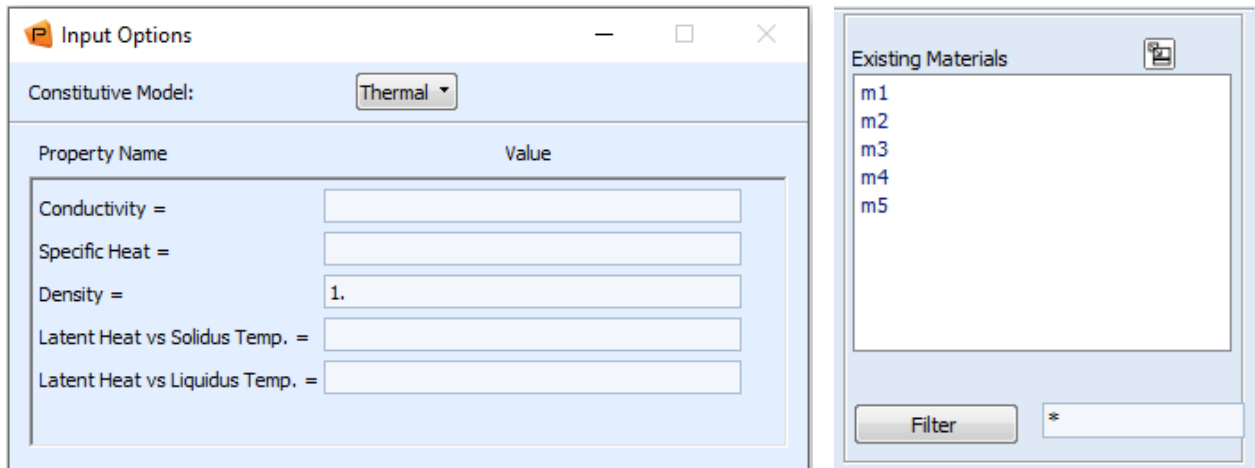
Figure 10 Screenshots of density given to different materials to act as ID tags.

3.1.3.2 Face Tags

All faces in the geometry need face tags, even internal faces between sections. WELDSIM uses the IDs to identify faces next to each other and to assign heat transfer coefficients between them. The way the faces are identified is by assigning heat flux numbers to each face in the geometry. Again, the heat flux given have no physical meaning in the simulation and is only used for identification. Illustrations and explanations can be found Appendix A.

10

3.2 WELDSIM

A simulation of this kind has never been done before. Therefore, in the beginning the approach used was to do a thorough review of the most similar simulation done in WELDSIM. Hallvard Fjaer, creator of WELDSIM, has done aluminium to steel lap joint simulations [28]. The simulation was done for the OPTIMALS project at SINTEF that HYB welding also is a part of. However, the welding process in that simulation was GMAW. Still, the WELDSIM code he wrote became a starting point for this project. A small portion of standard options where kept from this code. The other where changed to collaborate with the new geometry or changed to account for the difference between GMAW and HYB welding.

Without user interface many of the choices and options are hard to visualise and explain. So, the full input code for WELDSIM for this simulation can be found in appendix B with comments on important sections. This chapter will highlight some of the code. However, to get the full picture appendix B and user manual should be used [21].

The code starts with some parameters that are set and used throughout the rest of the code. Most of the parameters are straightforward and taken from the welding parameters. However, voltage and current are not directly used in HYB welding and cannot be directly imported. To find the heat input in the HYB process another approach must be used. Using the total power consumption of the welding tool and subtracting the heat losses. Total power consumption is calculated with Equation 1 using torque and rotational speed.

$$W_t \ = \ \frac{2\,\pi}{60} M_t \ \times \ N_s$$

Equation 1 Total power consumption from the welding tool

$W_t - Total\ power\ consumption\ in\ W$

$M_t - Mean\ torque\ on\ tool\ in\ Nm$

$N_s - Rotational\ speed\ in\ rpm$

The power consumed by the tool is estimated to be 3.3kW. However, not all the power consumed by the welding tool gets transferred to the weld. Heat transfer in HYB welding has previously been looked at in the PhD thesis of Aakenes U. R. where it was found that as much as 50% of the total power is lost to excessive friction between different moving extruder parts and their stationary counterparts [29]. This combined with the CO_2 cooling used in HYB welding that has an estimated cooling capacity of about 1kW [30]. Gives an estimate of 1.1kW transferred to the weld. And with Equation 2 a heat input of about 125 J/mm is found.

$$H_i \ = \ \frac{W_c}{v}$$

Equation 2 Heat input calculated from power consumed and welding speed

$H_i - Heat\ input\ in\ J/mm$

$W_c - Power\ consumption\ in\ W$

$v - Welding\ speed\ in\ mm/s$

Voltage and current are used in WELDSIM to calculate heat input thru Equation 3. And does not differentiate between ampere and volt. The amper and volts are therefore free to choose as long as H_i from Equation 3 equals 125 J/mm. Heat input parameters where therefore chosen as 15 volt and 75 ampere.

$$H_i = \frac{A \times V}{s}$$

Equation 3 Heat input calculated from voltage and current

$H_i - Heat\ input\ in\ J/mm$

$A - current\ in\ amps$

$V - Voltage\ in\ volts$

$s - Welding\ speed\ in\ mm/s$

The neutral file exported from Patran was the first thing included in the code. With that file all the elements and ID tags where imported. And could be used to give everything the correct properties and functions. The tags of the sections are used throughout the code to assign the needed properties and functions for the geometries in each module. Some examples can be seen in Figure 11. Where the ID is used to label the output data and also to import material data from external files, to be used in that specific module. Notice that the material data imported is not the same for thermal properties and alloy composition modules. For the thermal properties modified 6060 aluminium and DP600 is used to represent the aluminium and the steel. But in alloy composition the steel segments are given a 5183-aluminium composition as a dummy value. Because steel does not have a microstructural model in WELDSIM. WELDSIM needs a dummy value to run. However, the composition of the steel parts is discarded later in the code.

Module WriteResults		Module ThermalProperties		Module AlloyComposition	
		! Id Dataset names		! Id Data set	
GLviewExportLabel Alu-BM	1	1 AA6060T6_mod		1 HYB6082Base	
GLviewExportLabel Alu-HAZ	2	2 AA6060T6_mod		2 HYB6082Base	
GLviewExportLabel Weld-FM	3	3 HYB2filler		3 HYB6082Wire	
GLviewExportLabel Steel-BM	4	4 DP600		4 5183a	
GLviewExportLabel Steel-Backing	5	5 DP600		5 5183a	

Figure 11 Same ID tags used in different sections in the WELDSIM code depending on what the specific module needs

Welding module is probably the most important module in WELDSIM. For most welding simulations the heat is added to the filament material or wire in the welding process then dispersed and released into the surrounding material when the material is deposited. This can be simulated by adding heat to the areas that are not solid. So, the heat is added with the material in the void until the void is filled by the solid as the welding module moves along the weld. However, in the HYB process both filament material and stirring of aluminium base material is given heat input. To account for that the heat is added to the filler material as well as to the aluminium under the pin.

Heat input is added in three welding segments. As previously mentioned, the principles of double ellipsoidal heat transfer are used to account for shallow and deep heat transfers in normal welding. But in HYB simulation the increased flexibility gained by this is used to put one heat input ellipsoid in each of the sections under the pin. One in the void where the filament material is added and one in the aluminium base material (Figure 12). The ellipsoidal heat transfers are put close to the top of the weld. As that is where most of the heat is added. The third welding segment is put in the centre of the weld. And is representing a surface gaussian heat source over the whole area.
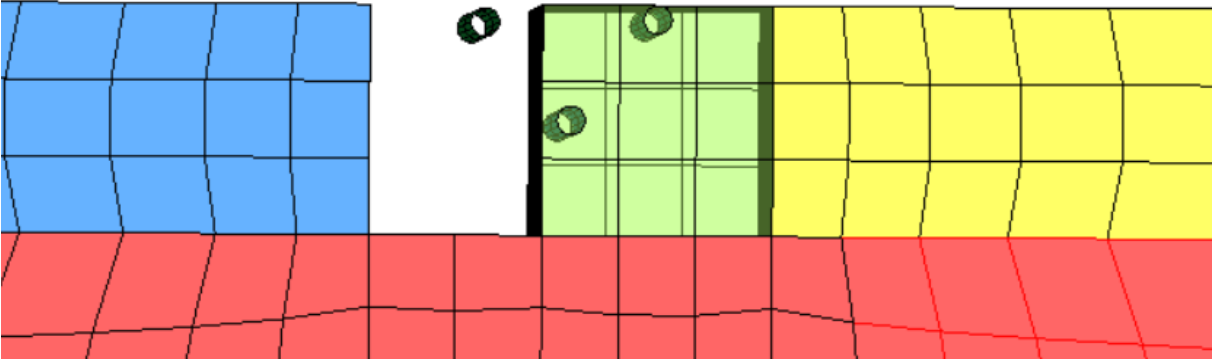
Figure 12 Close-up of the welding sone before simulation with welding segments included

Particle size distribution module is the module that makes WELDSIM a special weld simulation tool. This module is the largest and most important part of the microstructural model previously mentioned. It considers the nucleation, growth, coarsening and dissolution of the material throughout the process. The time it takes to weld the 500mm plates is just above 55 seconds. However, the simulation goes on for 3001 seconds to ensure that the thermal and microstructural models are done. After 3000 seconds room temperature ageing is applied to the model. Where pre-existing ageing data for alu6082 is imported from an external file and applied to the model.

There is a significant difference in volume between the real weld and the simulated geometry (Figure 13). To account for this in the regard of heat transfer and heat capacity the density of the wire metal that fills the void is increased by 20% in the mechanical properties module. This does not affect the material in any of the other modules.

a)

b)
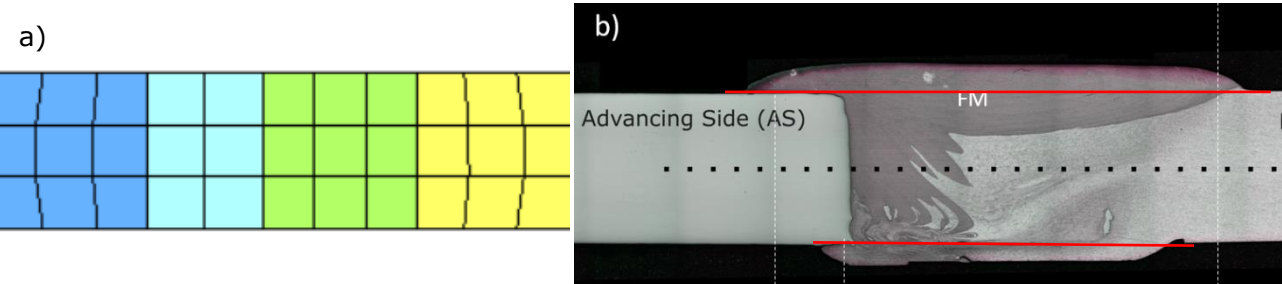
Figure 13 Figure showing difference in volume of a) simulated geometry and b) real life weld

4 Results from WELDSIM simulations

After simulations, the results are given in different files. One text file for each of the different outputs. With datapoints corresponding to the datapoint made in "Write Results" module of the code (Appendix B)

In addition to visual results in a GLview file. This chapter will present results from both GLview file and extracted results from text files.

4.1 Temperature

The most interesting results during welding is the temperature. A clear difference can be seen between aluminium and steel side of the weld. From Figure 14 we can see that the aluminium plate on the right of the weld has more prominent temperature lines than on the steel because of the good thermal conductivity in the aluminium. This cause the aluminium to absorb more of the heat input than the steel.
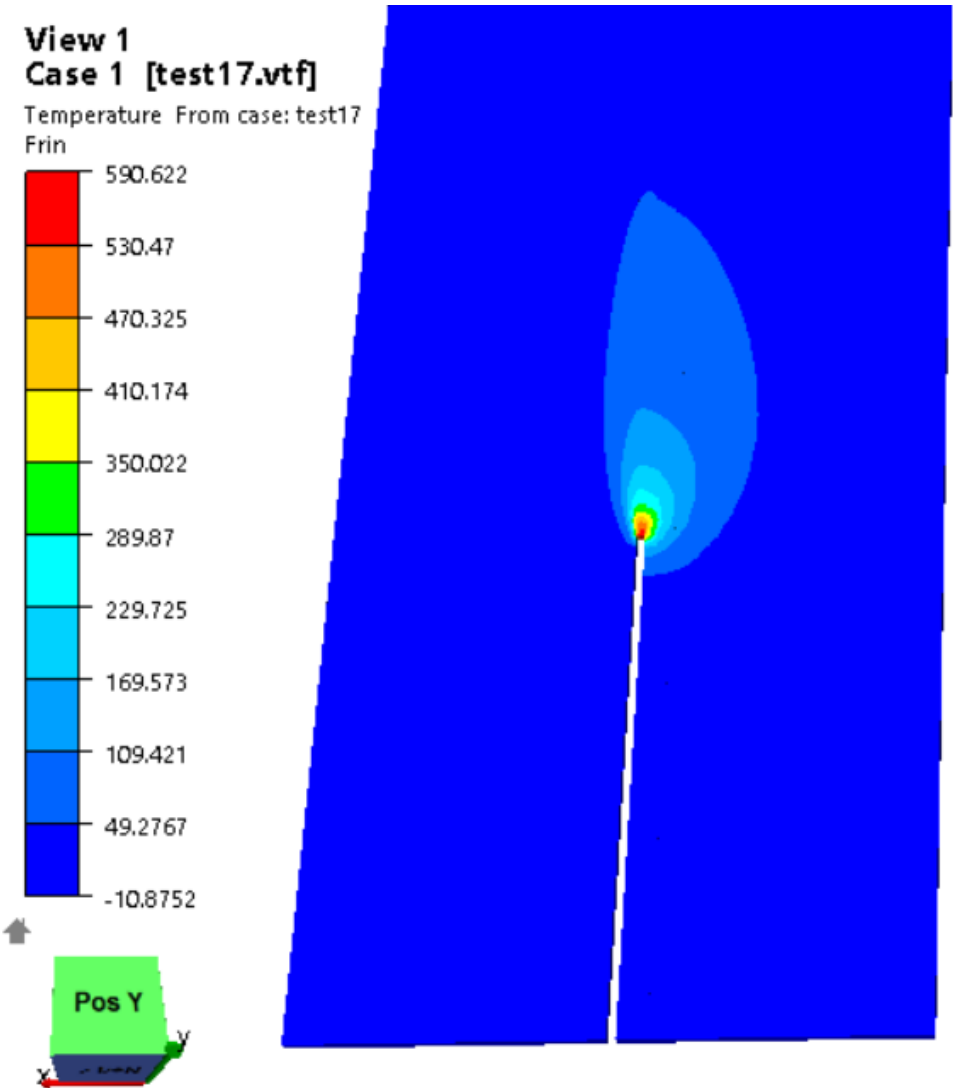
Figure 14 Temperature during welding from WELDSIM simulations

Peak temperature is about 600 degrees during welding (Figure 14). This is not a high peak temperature for welding in general. But still a bit higher than expected from HYB welding. HYB is a solid-state welding process and therefore a lower temperature was expected. However, the area of the peak temperature is small and total heat input is like the real-life process. The peak might come from a bit to small heat source area, but the simulations would not run with a larger area. Since the area with high temperature is so small and the temperature drops fast when the heat source passes. The influence from the peak will not be too large on the results.
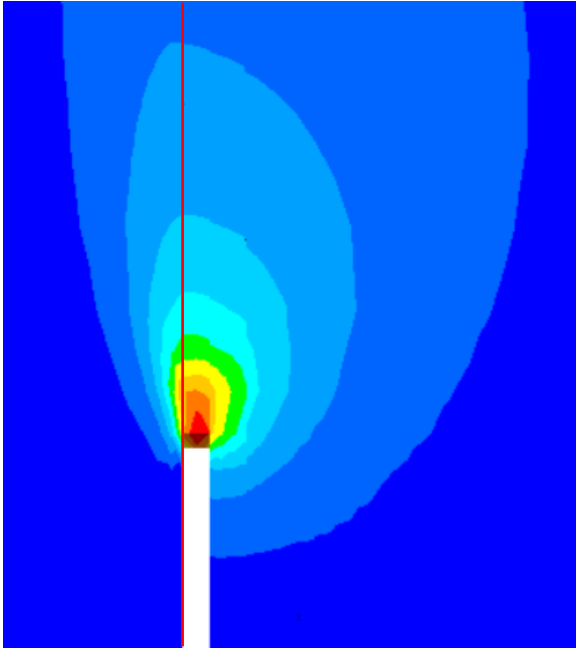
Figure 15 Close-up of the temperature during welding from WELDSIM simulations with a red line indicating the Al-Fe interface.

Notice from the close-up in Figure 15 that the heat from the weld "travels" in front of the weld. Making the aluminium heat up in front of the heat source in contrast with the steel. The temperature tail after the heat source is also significantly wider on the aluminium side of the weld. Some because the heat source is located on the aluminium side. But mostly because of the difference in thermal conductivity. At the end of simulation, the temperature is evenly distributed in the whole geometry at just above 20 degrees. Indicating that applying the data for room temperature ageing after 3000 seconds is acceptable.

The steel backing absorbs some heat. But the heat absorbed is significantly less than in both the aluminium and steel part of the weld (Figure 16). This is because of the heat transfer coefficient between the steel backing and the welded plates are different and lower than the coefficient between plates after they are welded.
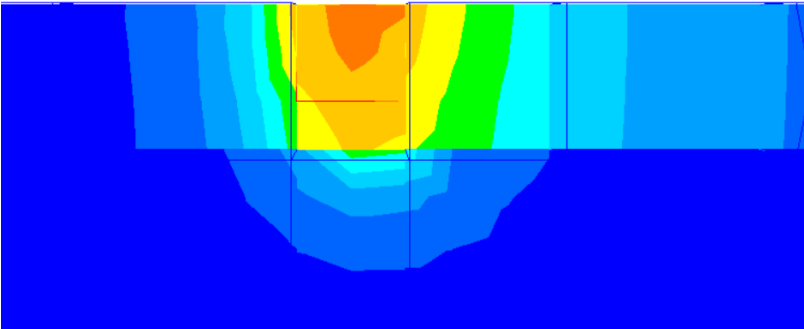
Figure 16 Cross section of temperature during welding from WELDSIM simulations with steel backing

4.2 Hardness

Harness data are taken after the room temperature ageing has been added. Steel hardness is just a "dummy" value in this simulation. Because WELDSIM does not include PSD model for steel yet. Furthermore, the steel does not influence the strength of the weld in any significant way. Strain and fracture will occur in the weaker aluminium and therefore aluminium is the interesting part of this simulation.

The results show that the process reaches "pseudo steady-state" welding relatively fast (Figure 18). With consistent material data close to the weld start. After 3mm of welding there are no major visual fluctuations to the hardness of the material. The hardness is then stable until the end where it changes some. This is expected because the heat cannot travel ahead of the weld as previously mentioned and will therefore help change the temperature some. Figure 17 shows the softening at the end of the weld. The softening is only visible in the last 15mm of the weld.
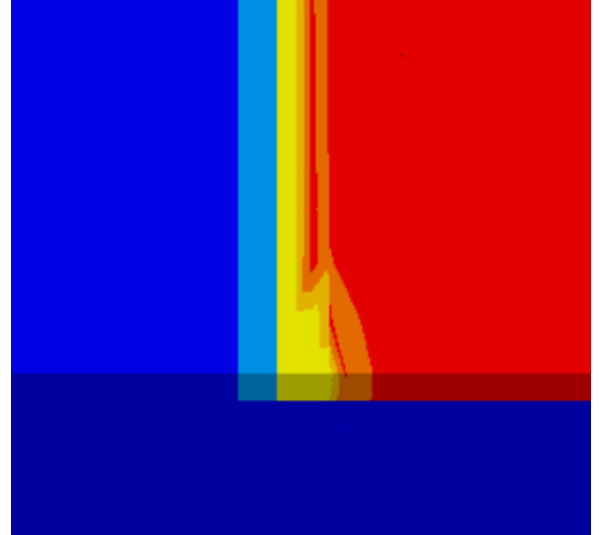
Figure 17 Hardness illustration at the end of the weld taken from WELDSIM simulation
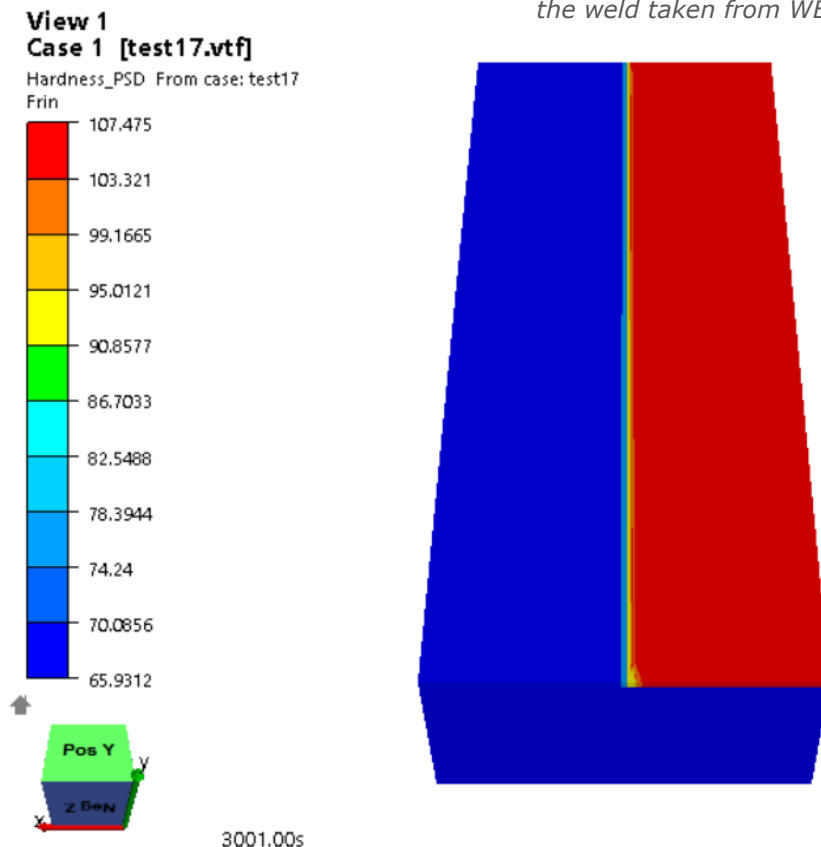
Figure 18 Hardness illustration of the whole geometry taken from WELDSIM simulations

The hardness in the cross section is interesting. Because there are already hardness data on this weld contained from testing by Lise Sandnes. Hardness from testing was obtained by cutting a HYB Al-Fe weld like the one in this project in test samples then doing hardness testing on the cross section every millimetre along the section and in three different heights. One in the centre, 1mm over and 1mm under centre of the plates. The test data can be seen in Figure 19.
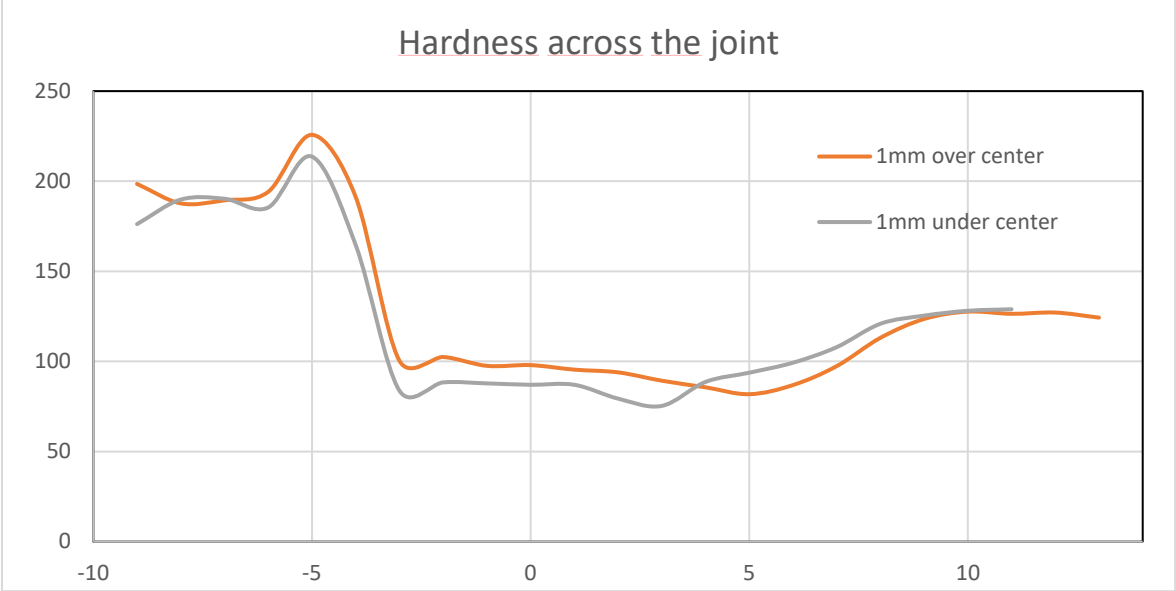
Figure 19 Hardness data plot for 1mm over and 1mm under centre of the weld. Made using Lise Sandnes` test results (Personal Communication 2019), plot taken from [3]
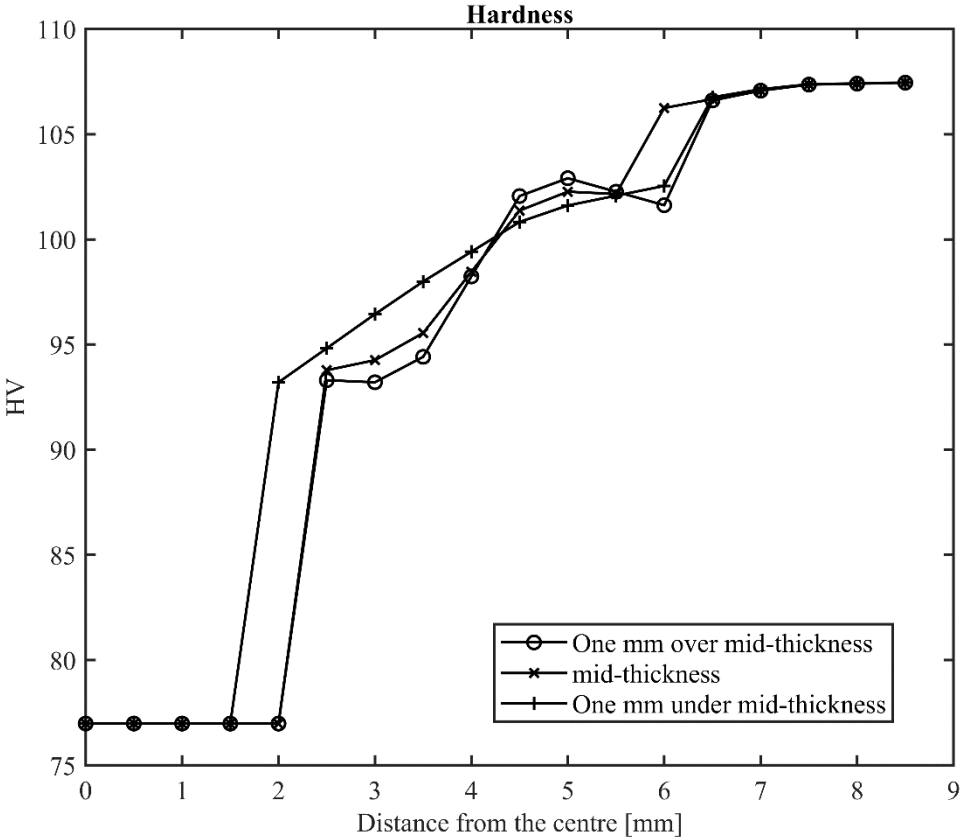
Figure 20 Hardness data plot from WELDSIM simulations showing the hardness in the cross section of the weld

17

Datapoints where chosen in the simulation to make a similar hardness curve (Figure 20). This simulation does not include hardness data for the steel part of the weld. However, lowest hardness and strength are within the aluminium, making the steel side of less importance. The plot from WELDSIM simulations have some differences compared to the test results, especially close to the welding sone. There are a lot of work hardening done by the tool during welding that the simulation does not include. This might explain the difference close to the Al-Fe interface. The hardness level is also different. With a max hardness in the aluminium of about 125 HV in the tests and 107HV in the simulations. This can be explained by differences in the material to begin with, and inaccuracies in the hardness test bench. However, there are also some clear similarities between the plots. From about 3mm into the weld the hardness curves within the plots are relative to each other. Indicating that the HAZ that has previously been shown to have an incline [3]. Might have a similar incline in these simulations. This can be interpreted by that the weakest point is below centre close to the weld. Further from the weld the line above the weld is weakest. Making it probable that the hardness is very similar to test results if work hardening is included. However, this cannot be concluded before work hardening is included in the simulations. Work hardening will flatten the hardness plot by having highest influence close to the Al-Fe interface. But to include work hardening is not an option in WELDSIM for now.

4.3 Residual stress

The residual stress after welding can be seen in Figure 21. The stresses are probably a bit inaccurate in this simulation set-up. The thermo mechanical simulations for this type of weld are not good enough yet but Hallvard Fjaer, creator of WELDSIM, is working on implementing a new version of this. This together with the lack of work hardening in the welding segment make the stress results unreliable. However, the stresses seem to be higher in the expected regions giving implications that the stress field might not be far off when the program is updated (Figure 22).
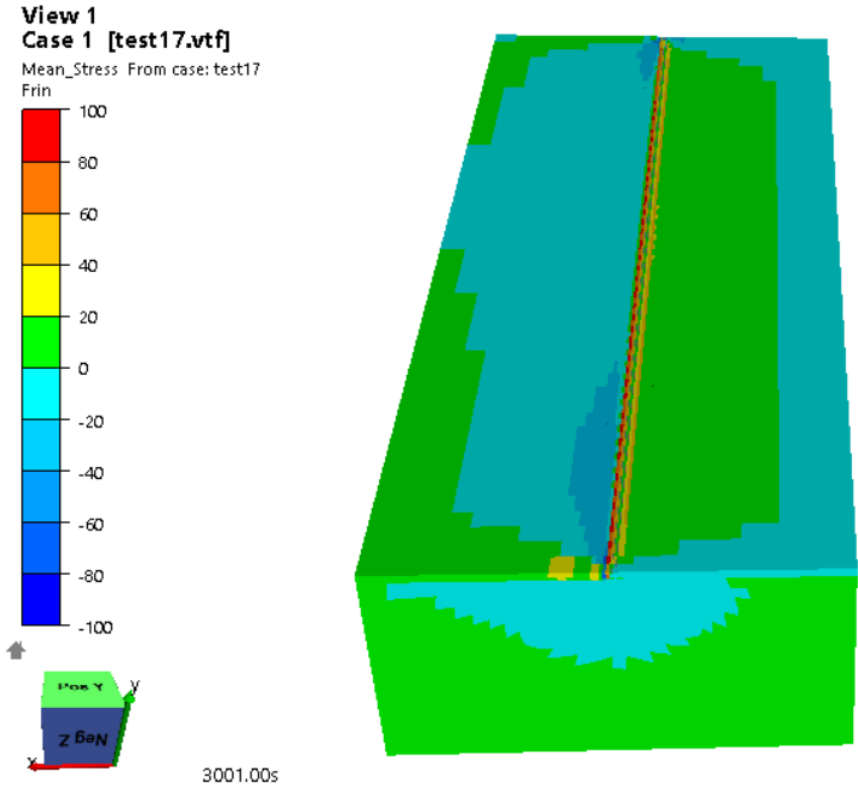
Figure 21 Residual stresses after welding from WLEDSIM simulation
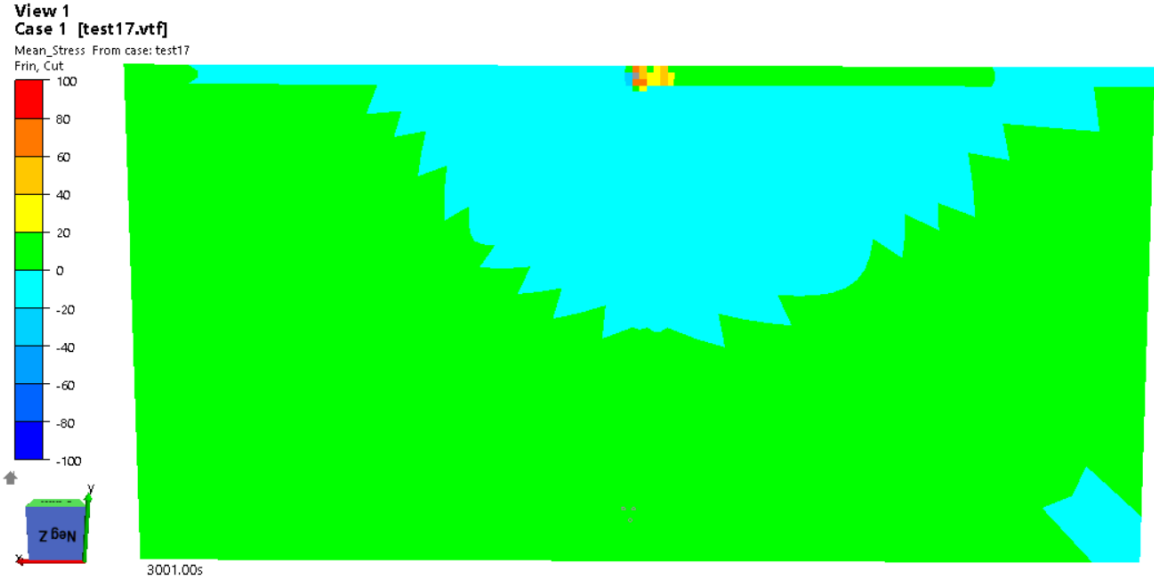
Figure 22 Cross section of residual stress after welding in WELDSIM simulations

19

4.4 Displacement

The displacement from the simulations are relatively small. With max distortions in the BM-plates of about 1.5mm (Figure 23). This can be explained by the fact that the plates are clamped to the steel backing throughout the welding simulation. And therefore, might be larger if the boundary is modified. However, the distortions are not expected to be large in HYB welding as the temperature is low.
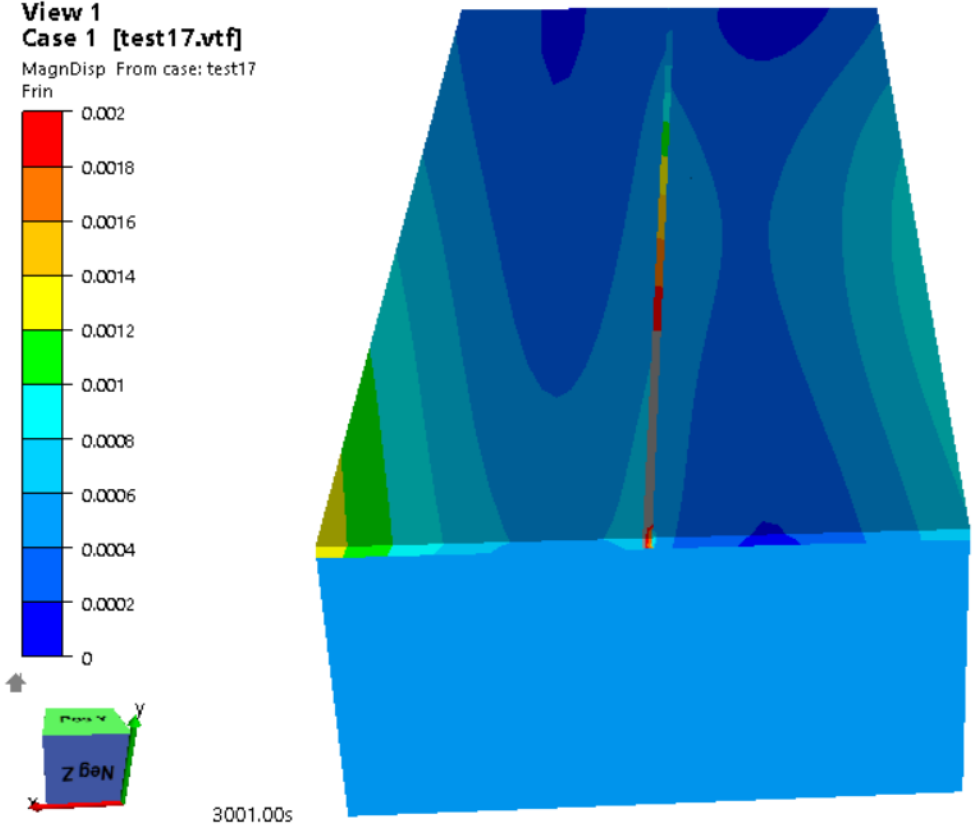
Figure 23 Displacement from WELDSIM simulations

5 Conclusion

One of the main objectives of this project was to simulate the welding process itself. And get results that can be used for further development of the HYB process. The welding simulation shows some great promise. With realistic heat patterns and comparable hardness. Still there are some work left before the simulations can be said to be realistic. And before results from the simulation can directly be used in development of the HYB process.

When the model has been set up correctly and WELDSIM has added the needed features. The simulations can be used to see how different inputs in the welding process will affect the results. This can save time in further development of the process. By doing many simulations on different welding speeds, wire rates, and rotational speeds on the tool, an optimal setup of the process might be found faster using simulations. The benefits from having this possibility would be notable for development of the welding process.

Another element of this thesis was to investigate if WELDSIM simulations are applicable to be used in HYB-weld simulations. For that, the conclusion must be divided. WELDSIM with its many attributes fitting such simulations are a great prospect. However, the time it takes to do a WELDSIM simulation might not equal the results that is possible to obtain at this time. But with the updates under work, good dialogue and cooperation with the creator of WELDSIM it is very possible that WELDSIM simulations will be a great tool for further work.

Further work

Some further work on the simulation is needed and is already under way. The dialogue with Hallvard Fjaer, the creator of WELDSIM. Has been important throughout the project. Currently he is working on a new thermomechanical simulation model with new data sets. As well as a feature letting users include a pressure while welding. Making it possible tp replicate the pressure from the tool in HYB welding.

There is currently also work being done on a Al-Al HYB-weld simulation using WELDSIM. Some knowledge from that work might be useful in completing the Al-Fe simulations.

When the needed data like residual stresses and mechanical properties is available. The model presented in the project work [3], can be used to simulate ductile fracture more accurately and with some modifications fatigue behaviour of the weld.

6 References

1. Soo, V.K., et al., *Sustainable aluminium recycling of end-of-life products: A joining techniques perspective.* Journal of Cleaner Production, 2018. **178**: p. 119-132.
2. Worldwide, D., *Aluminum Content in North American Light Vehicles 2016 to 2028.* Ducker Worldwide, Troy, MI, 2017.
3. Teige, A., *FE Simulation of the Fracture Behaviour of AluSteel Butt Welds Produced Using the Hybrid Metal Extrusion and Bonding (HYB) Process* 2019, NTNU.
4. Mathiasson, M., *'An In-Depth Analysis of the Bond Strength of a Dissimilar Al-Fe HYB (Hybrid Metal Extrusion & Bonding) Joint*. 2019, NTNU.
5. Lumley, R., *Fundamentals of aluminium metallurgy: production, processing and applications*. 2010: Elsevier.
6. Mrówka-Nowotnik, G., J. Sieniawski, and M. Wierzbińska, *Analysis of intermetallic particles in AlSi1MgMn aluminium alloy.* Journal of Achievements in Materials and Manufacturing Engineering, 2007. **20**(1-2): p. 155-158.
7. Rethwisch, D.G., *William D. Callister, Jr.* Materials Science and Engineering. **3**.
8. Grong, Ø., L. Sandnes, and F. Berto, *Progress in solid state joining of metals and alloys.* Procedia Structural Integrity, 2019. **17**: p. 788-798.
9. Shi, Y., et al., *Pulsed double-electrode GMAW-brazing for joining of aluminum to steel.* Weld. J, 2014. **93**(6): p. 216-224.
10. Watanabe, T., H. Takayama, and A. Yanagisawa, *Joining of aluminum alloy to steel by friction stir welding.* Journal of Materials Processing Technology, 2006. **178**(1-3): p. 342-349.
11. Yang, S., et al., *Welding of aluminum alloy to zinc coated steel by cold metal transfer.* Materials & Design, 2013. **49**: p. 602-612.
12. Tanaka, T., T. Morishige, and T. Hirata, *Comprehensive analysis of joint strength for dissimilar friction stir welds of mild steel to aluminum alloys.* Scripta Materialia, 2009. **61**(7): p. 756-759.
13. Gullino, A., P. Matteis, and F. D'Aiuto, *Review of aluminum-to-steel welding technologies for car-body applications.* Metals, 2019. **9**(3): p. 315.
14. Praveen, P. and P. Yarlagadda, *Meeting challenges in welding of aluminum alloys through pulse gas metal arc welding.* Journal of Materials Processing Technology, 2005. **164**: p. 1106-1112.
15. Sensharma, P., M. Collette, and J. Harrington, *Effect of welded properties on aluminum structures.* Ship Structure Committee Report 2011, 2011.
16. Sigworth, G.K., *Gas Fluxing of Molten Aluminum: An Overview and Update.*
17. Etherington, C., *CONFORM—a new concept for the continuous extrusion forming of metals.* 1974.
18. Sandnes, L., et al., *Assessment of the Mechanical Integrity of a 2 mm AA6060-T6 Butt Weld Produced Using the Hybrid Metal Extrusion & Bonding (HYB) Process–Part II: Tensile Test Results.* Procedia Structural Integrity, 2019. **17**: p. 632-642.
19. Myhr, O., et al., *WELDSIM- an advanced simulation model for aluminium welding.* NIST Special Publication(USA), 2000. **949**: p. 52-63.
20. Goldak, J., A. Chakravarti, and M. Bibby, *A new finite element model for welding heat sources.* Metallurgical transactions B, 1984. **15**(2): p. 299-305.
21. IFE, W., *WELDSIM Reference Manual* in *Version 8 Release 07*, IFE, Editor. 2019.
22. Myhr, O., et al., *Modeling of microstructure evolution, residual stresses and distortions in 6082-T6 aluminum weldments.* WELDING JOURNAL-NEW YORK-, 1998. **77**: p. 286-s.
23. Myhr, O. and Ø. Grong, *Modelling of non-isothermal transformations in alloys containing a particle distribution.* Acta Materialia, 2000. **48**(7): p. 1605-1615.

24.   Myhr, O. and Ø. Grong, *Novel modelling approach to optimisation of welding conditions and heat treatment schedules for age hardening Al alloys.* Science and technology of welding and joining, 2009. **14**(4): p. 321-332.
25.   Myhr, O., Ø. Grong, and S. Andersen, *Modelling of the age hardening behaviour of Al–Mg–Si alloys.* Acta Materialia, 2001. **49**(1): p. 65-75.
26.   Myhr, O., et al., *Modelling of the microstructure and strength evolution in Al–Mg–Si alloys during multistage thermal processing.* Acta Materialia, 2004. **52**(17): p. 4997-5008.
27.   mscsoftware.com. *Patran*. 2020   [cited 2020 12.06.2020]; Available from: https://www.mscsoftware.com/product/patran.
28.   Fjaer, H., *Personal communication*. 2020.
29.   Aakenes, U.R., *Industrialising of the Hybrid Metal Extrusion & Bonding (HYB) Method–From Prototype Towards Commercial Process.* 2013.
30.   Sandnes, L., *Al-Al butt weld 2017-02-23_2 – Summary of experimental conditions To be examined by Lise Sandnes in her MSc thesis*. 2017.

Appendix A

Patran

This appendix will give a detailed walkthrough on what pre-processing was done in Patran prior to the welding simulations in WELDSIM. The idea while making this appendix is to give the reader a better understanding of what has been done. And to make it easier for others to recreate this simulation and to make other simulations in WELDSIM.

For the menus needed to show up, we need to change the analysis preferences settings to ABAQUS and thermal, by doing as shown below.

Menu > Preferences > Analysis
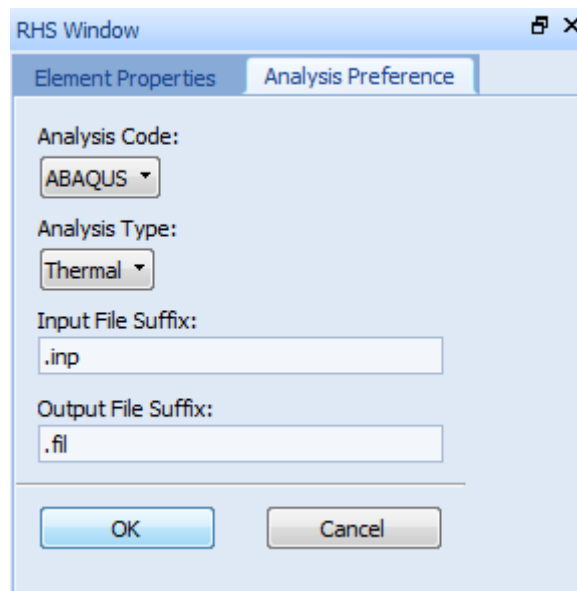
Menu for changing the "analysis preference" settings in Patran

Making of the Geometry

The drawing of the geometry was quite normal. In this project the geometry was relatively simple and rectangular. Therefore, the different sections where made by drawing up planes and extruding them into solids.

Assigning identification tags

The identification tags needed for WELDSIM to interpret the file where made in Patran. The values given as identification tags have no physical meaning and are only used to identify different sections or faces. Firstly, the different sections in the geometry where given IDs. By making one material for each section with a density of 1 to 5. By going into geometry, choosing properties and isotropic. This is repeated until there is one material for each section.

Geometry

Properties > isotropic
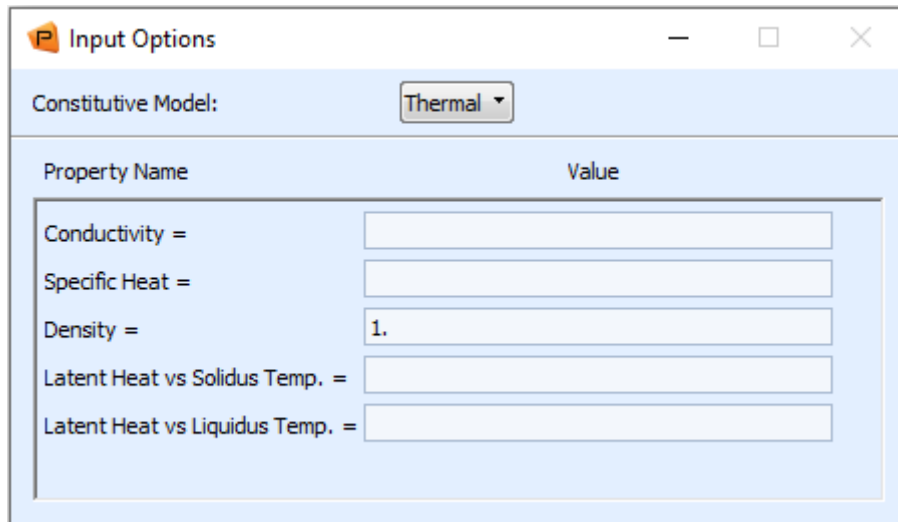
Menu for assigning density
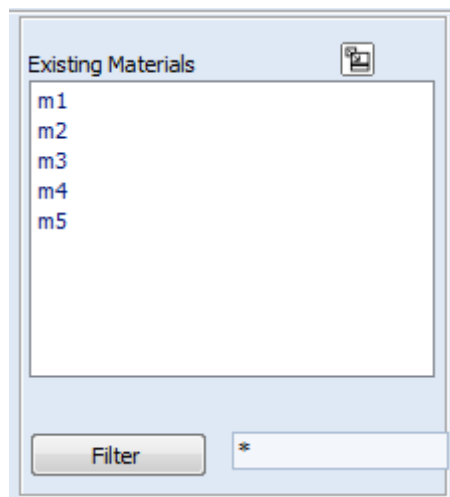
List of materials

When all the materials where made they need to be assigned, one to each property set. Before using "application region" to apply the property set to the associated section of the geometry.
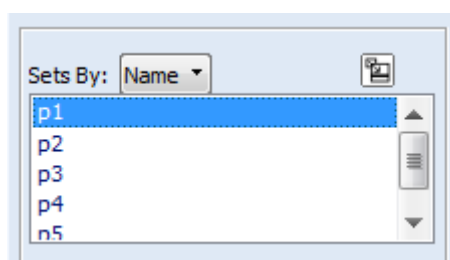
List of property sets.

With the ID tags for the sections done we move on to the face tags. Each face in the geometry needs an ID tag, just like the sections. Even the internal interfaces between different sections need an ID. This is done by assigning heat flux values to each face. Since there are a lot of faces in a normal geometry its important to find an intuitive way to give and remember the values for each face.

The face tags are made in Loads/BCs menu and then choosing "Heat Flux" then Create heat flux. Internal interfaces need individual ID tags for each side of the interface. For example, the interface between aluminium base material and steel backing need individual ID tags from each side. The aluminium face against the steel and the steel face against the aluminium. However, all the faces against air, the outer faces. Can have a common ID. And if given a common ID, will make it easier in the WELDSIM programming.
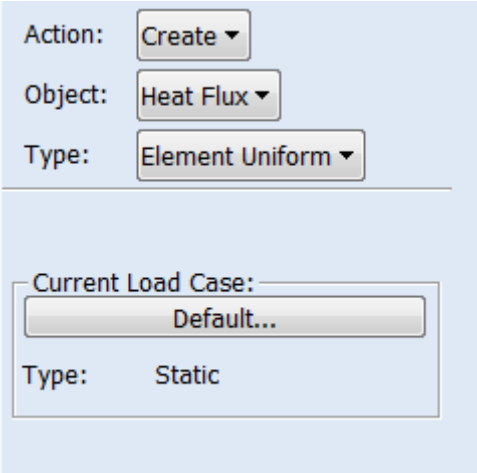
Menu for creating heat flux

The naming method of the faces in this project have been. First the section the face is on. Then the section it is facing. For example, the steel welding plate is section 4. And the weld is section 3. So, the steel face against the weld is named 4-3. Each of the faces get heat flux numbers from 1-18. By naming them after position its easier to find the right ID tag when matching correct faces in the WELDSIM code. As seen in the figure below section 5 have a few different names. These come because of internal interfaces in the same section. The last heat flux "out" is all the outer faces in the geometry and will be used to add air cooling in the simulation.

Existing Load/BCs

1-2
1-5
2-1
2-3
2-5
3-2
3-4
3-5
4-3
4-5
51-52
52-51
52-53
53-52
53-54
54-53
5top
out

| Filter | * |
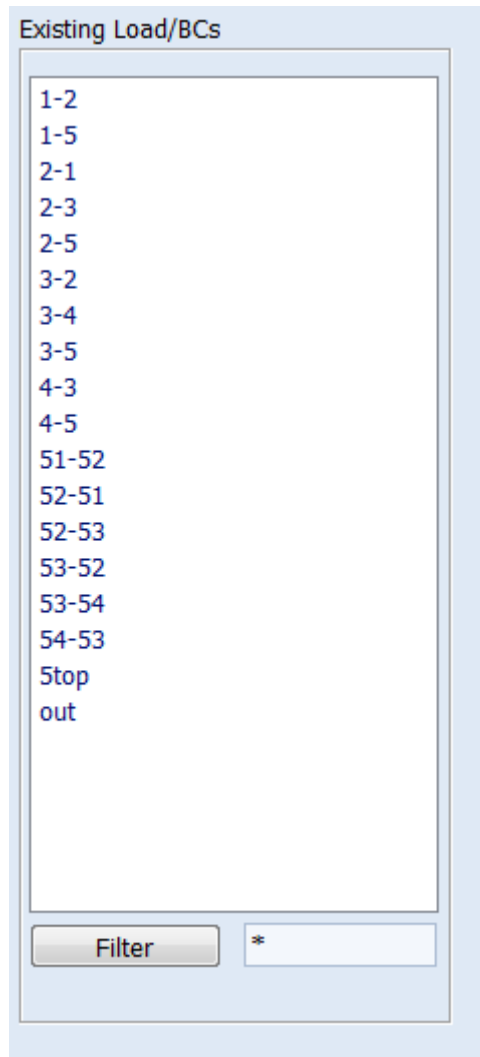
List of faces with different heat flux numbers

Mesh

Meshing of the geometry was quite ordinary. Starting with a mesh seed with global edge length of 10mm. Keeping large elements far from the weld and gradually decreasing element size closer to the weld. With the elements inside and right next to the weld with a size of around 1.5mm This gives a faster simulation without affecting the results too much. Linear hex elements where used throughout the model.
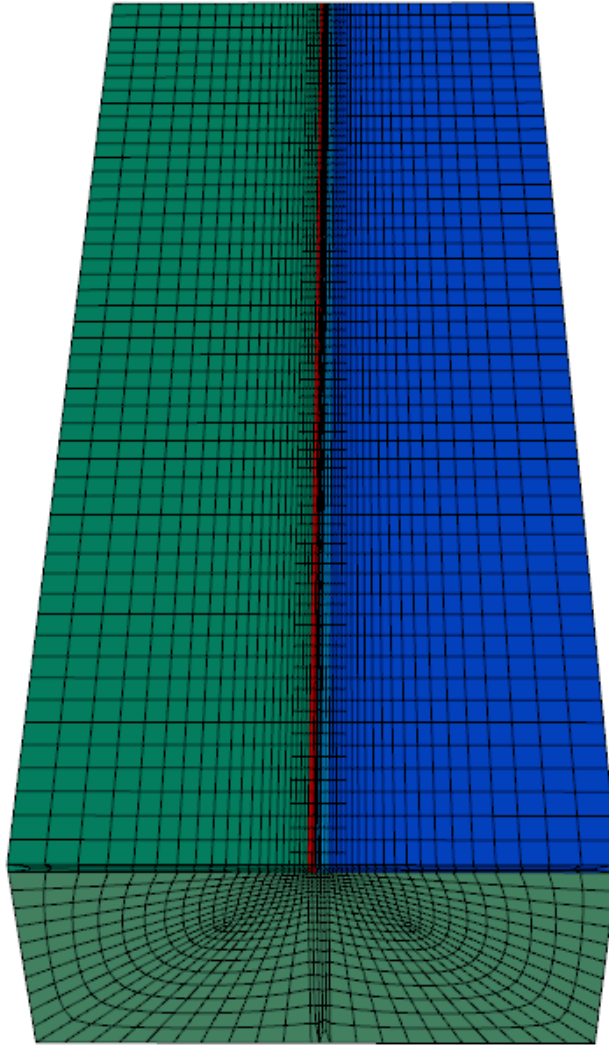
Illustration of the mesh made in Patran

Appendix B

WELDSIM

This Appendix is the input file that is read by WELDSIM to do the simulation. The code is split into modules. Some of the lines in the code will be explained and thoughts behind values will be given here. More information about specific functions in WELDSIM can be found in the WELDSIM reference manual [21]. Writing after exclamation points are comments and have no meaning in the simulation.

!===!

! Firsly there are a lot of variables given different values for use later in the script.

$END   3001.0   ! How many seconds the simulation will run, (not computing time)

$CASE Test17\Test17

$AmbTemp   20.0   ! c

$SteelThickness 4.0   ! mm

$AluThickness   4.0   ! mm

$Voltage   15   ! V

$Current   75   ! A   15V and 75A equals an heat input of 75W/mm

$WeldingSpeed   9.0   ! mm/sec

$WireSpeed   5.403310318   ! m/min

$Offset   0.0   ! mm

$BW   {18.849555922*&WireSpeed/(&WeldingSpeed*&AluThickness)   -0.5*&AluThickness}

$ArcEffScale { (1100.0 - &Current) / 1000.0 }   ! Scaling = 1 for 100 A, 0.95 for 150 A, 1.05 for 50 A

!===!
! Module that names and chooses placement of output files.

Module InputOutput

Overwrite

Home Dir   = C:\Users\audun\OneDrive\Desktop\Weldsim\Output_files\Test_A2S_backing_ny

Common Output File = &CASE&.txt

ErrorOutputFile   = &CASE&.err

MonitoringLevel   = 2

1

EndModule

!===!

Module Weldsim

Threads 4

meshfiletype   1

PatranFile
C:\Users\audun\OneDrive\Desktop\Weldsim\weldsim_software\inpfiles\neu\al-fe-backing.out

! Gathering the neutral file exported from patran containing geometry, mesh and ID tags

NoCompatibleGapMesh

NonCompFaceAngleTol 20.0

NonCompFaceDistTol   0.0005

ThermalProblem   !

! MechProblem   ! These choose what simulations to run or leave out.

NoMechProblem   !

ScaleGeom   0.001

        Pardiso4LiqStress

! CheckInputOnly

EndModule

!===!

Module WriteResults

! Choosing how often results are written in the output files. Starting with every half second during welding and increasing spacing as time goes on.

GenericNameResult = &CASE

LogEvent   0.0

LogFrequency   2.0

LogEvent   60.0

LogFrequency   0.5

LogEvent   70.0

LogEvent   100.0

LogFrequency   0.01

```
LogEvent          1000.0
LogFrequency     0.005   !!
LogEvent          3000.0
LogEvent           &END
logfileordring  = 2
```

! Selecting logpoints. The logpoints are trategcaly placed in the geometry to capture wanted differences in the weld.

```
logpoint       0.103 0.001 0.3
logpoint       0.1025        0.001 0.3
logpoint       0.102 0.001 0.3
logpoint       0.1015        0.001 0.3
logpoint       0.101 0.001 0.3
logpoint       0.1005        0.001 0.3
logpoint       0.1    0.001 0.3
logpoint       0.0995        0.001 0.3
logpoint       0.099 0.001 0.3
logpoint       0.0985        0.001 0.3
logpoint       0.098 0.001 0.3
logpoint       0.0975        0.001 0.3
logpoint       0.097 0.001 0.3
logpoint       0.0965        0.001 0.3
logpoint       0.096 0.001 0.3
logpoint       0.0955        0.001 0.3
logpoint       0.095 0.001 0.3
logpoint       0.0945        0.001 0.3
logpoint       0.094 0.001 0.3
logpoint       0.0935        0.001 0.3
```

```
logpoint       0.103 0.002 0.3
logpoint       0.1025        0.002 0.3
logpoint       0.102 0.002 0.3
logpoint       0.1015        0.002 0.3
logpoint       0.101 0.002 0.3
```

logpoint   0.1005   0.002 0.3
logpoint   0.1   0.002 0.3
logpoint   0.0995   0.002 0.3
logpoint   0.099 0.002 0.3
logpoint   0.0985   0.002 0.3
logpoint   0.098 0.002 0.3
logpoint   0.0975   0.002 0.3
logpoint   0.097 0.002 0.3
logpoint   0.0965   0.002 0.3
logpoint   0.096 0.002 0.3
logpoint   0.0955   0.002 0.3
logpoint   0.095 0.002 0.3
logpoint   0.0945   0.002 0.3
logpoint   0.094 0.002 0.3
logpoint   0.0935   0.001 0.3

logpoint   0.103 0.003 0.3
logpoint   0.1025   0.003 0.3
logpoint   0.102 0.003 0.3
logpoint   0.1015   0.003 0.3
logpoint   0.101 0.003 0.3
logpoint   0.1005   0.003 0.3
logpoint   0.1   0.003 0.3
logpoint   0.0995   0.003 0.3
logpoint   0.099 0.003 0.3
logpoint   0.0985   0.003 0.3
logpoint   0.098 0.003 0.3
logpoint   0.0975   0.003 0.3
logpoint   0.097 0.003 0.3
logpoint   0.0965   0.003 0.3
logpoint   0.096 0.003 0.3
logpoint   0.0955   0.003 0.3
logpoint   0.095 0.003 0.3
logpoint   0.0945   0.003 0.3

logpoint   0.094 0.003 0.3

logpoint   0.0935   0.001 0.3

! Frequency and ID of results given in the visual output file, in this case a GLview file.

GLview   2

BinGlview

ResultEvent   0.0

ResultFrequency   2.0

ResultEvent   60.0

ResultFrequency   0.5

ResultEvent   100.0

ResultFrequency   0.01

ResultEvent   500.0

ResultFrequency   0.005 !!

ResultEvent   1000.0

ResultEvent   2000.0

ResultEvent   3000.0

ResultEvent   3001.0

ResultEvent   5000.0

VtkOutput 0

OneElementBlock4EachID

GLviewExportLabel 1   Alu

GLviewExportLabel 2   Alu

GLviewExportLabel 3   Weld

GLviewExportLabel 4   Steel

GLviewExportLabel 5   Steel

EndModule

!==!

! Choosing size of timesteps in the calculations. There are a lot more calculations being done than there are output points. The intermediate calculations are there to secure correct results. Time steps increase as time goes in the simulation to speed up the simulation.

Module TimeStepping

TimeStartAndStop   0.0   &END

InitDeltaTimeTherm   0.01

MaxTempRateTherm   1.

DeltaTimeThermMinAndMax   0.01   20.0   !0.002

DeltaTimeThermMagnAndReduc 2.0   0.2

InitDeltaTimeMech   = 0.1

DeltaTimeMechMinAndMax   = 0.1   40.0

DeltaTimeMechMagnAndReduc = 8.0 0.3

MaxTempRateMech   = 20.0

EndModule

!===!

! Extracting thermal properties from an other text file,

Module ThermalProperties

EnthalpyMethod

DataFile
C:\Users\audun\OneDrive\Desktop\Weldsim\weldsim_software\inpfiles\idb\ThermProp.txt

ReferenceMaterial HYB2filler ! HYBfiller

! Id   Dataset names

1   AA6060T6_mod

2   AA6060T6_mod

3   HYB2filler   ! Thermal properties to the filament wire made for this simulation

4   DP600

5   DP600

EndModule

!===!

Module ThermalBoundaryConditions

NoErrorIfNoBoundaryID

!   BID Code Data

12   202 Air_cool !Symmetry 101 [0.0   20.0]

! Outer faces on the geometry get air cooling. Relatively small compared with internal heat transfers but will still have a contribution.

! All the faces in the geometry are given fixed heat transfer coefficient.

1 101 [0.0 20.0]

2 101 [0.0 20.0]

3 101 [0.0 20.0]

4 101 [0.0 20.0]

5 101 [0.0 20.0]

6 101 [0.0 20.0]

7 101 [0.0 20.0]

8 101 [0.0 20.0]

9 101 [0.0 20.0]

10 101 [0.0 20.0]

11 101 [0.0 20.0]

13 101 [0.0 20.0]

14 101 [0.0 20.0]

15 101 [0.0 20.0]

16 101 [0.0 20.0]

17 101 [0.0 20.0]

18 101 [0.0 20.0]

! The different faces are then coupled with their respected counterparts in internal interfaces the heat transfer coefficient used are very large. As the interface should not stop the heat transfer. Because, the heat transfer should be determined by the material properties and not internal boundaries.

interface 1 14 1101 [0.0   20.0]

interface 1 2 1101 [200000.0   20.0]

interface 3 4 1101 [200000.0   20.0]

interface 5 6 1101 [200000.0   20.0]

interface 13 14 1101 [200000.0   20.0]

interface 15 16 1101 [200000.0   20.0]

interface 17 18 1101 [200000.0   20.0]

! These heat transfer coefficients are set lower. Representing the interface between welded plates and steel backing.

interface 7 11 1101 [2000.0   20.0]

interface 8 11 1101 [2000.0   20.0]

interface 9 11 1101 [2000.0   20.0]

interface 10 11 1101 [2000.0   20.0]

Inliningdatasets

DataGroup PeakTempDepAlfa

0.0   100.0

600.0   100.0

655.0   200000.0

700.0   200000.0

EndData

DataGroup Air_cool

!   Ambient Temperature

&AmbTemp

! Temp   alfa

23.0   4.

43.0   6.

123.0   8.

223.0   11.

623.0   18.

800.0   25.

EndData

DataGroup YdepUnder

0.0   -3

0.015 -4

EndData

EndModule

!===!

Module ThermalFields

InitialTemperature   20.0

1   20.0

2   20.0

3   500.0

 ! The initial temperature of the added material is higher to ease the simulation this has no impact on the heat input. As the heat needed to increase temperature from 20 to 500 degrees are taken into account.

4   20.0

5   20.0

EndModule

!===!

Module Welding

ExactMassFeed

NumHeatEffCheck

SeparateHeatAccEachSource

Nofillfromroot

! novolheatfullysolid

IdNoHeat 1

IdNoHeat 4

IdNoHeat 5

IdFiller 3

! Heat from the welding are only directly added to the welding zone under the pin. The heat then disperse into the different materials. Similar to the real welding.

MinAndMaxArcEff   0.001   80.0

MinAndMaxWarnArcEff 0.0   20.0

FilletHeatBoost   15

NoWeldLineMirrorSymmetry

Default FactorHeatFront = 1

DefaultSurfTolerAngle   70.0

DefaultFracHeatHomogeneous 0.59

! Welding segments. The heat is added by the principles of double ellipsoidal heat transfer, determined here by the source type.

NewSegment

      WireDiameter 0.002

      WireSpeed   { 9.0* 0.03819718634 / 10.0 }

      StartTime   0.0

      SourceType   1

      Velocity   { 0.001 * &WeldingSpeed }   ! mm -> m

EllipsoidAxes 0.007 0.003 0.005 0.003

! Transversal, normal, rear and front size of the ellipsoid adding heat to the welding segment

      Voltage   &Voltage   ! using the parameters set in the start of the script.

      Current   &Current

ArcHeatEff   { &ArcEffScale * 0.55 }

      SegmentType   1

    StartPosition 0.1005 0.0038   0.5

    StopPosition   0.1005 0.0038   0.0

    NormDirection 0.0 1.0 0.0

    ellipsoidtransversersecutoff 0.0015

! Choosing the positioning and direction of the welding. Here it is a straight line.

NewSegment

      StartTime   0.0

      SourceType   1

      Velocity   { 0.001 * &WeldingSpeed }   ! mm -> m

EllipsoidAxes 0.007 0.003 0.005 0.003 ! Transversal, normal, rear and front

      Voltage   &Voltage

      Current   &Current

ArcHeatEff   { &ArcEffScale * 0.1 }

      SegmentType   1

    StartPosition 0.099 0.0038   0.5   ! 0.1005   0.002   0.5

StopPosition   0.099 0.0038   0.0   !   0.1005   0.002   0.0

NormDirection   0.0 1.0 0.0

ellipsoidtransversersecutoff 0.002

! Notice the positioning of the two ellipsoids are different. This is done to more evenly distribute the heat transfer in the welding sone. The first one is set in the void of the weld (where material is added). And the second one is set in the AL-BM under where the pin is stirring the material

NewSegment

! This segment represents the surface heat added in the process. The contribution of this heat source is a lot smaller. However, it still contributes to get more realistic heat input.

StartTime   0.0

SourceType   =   2

Velocity   { 0.001 * &WeldingSpeed }   ! mm -> m

Voltage   &Voltage

Current   &Current

ArcHeatEff   { &ArcEffScale * 0.17 }

SurfSigma   0.004

SurfTolerance   0.0032

SegmentType   1

StartPosition 0.0995   0.002   0.5

StopPosition   0.0995   0.002   0.0

NormDirection 0.0 1.0 0.0

ellipsoidtransversersecutoff 0.002

EndModule

!===!

Module NumericalIntegrationThermal

! BothWeldHeatAndHeatLoss

! ShowRpdBeadInteraceHeatFlux

heatfillfurgecrit 100000000.0

EndModule

11

!===!

! Module collecting material composition in different materials to use later in the simulation of microstructural changes depending on the temperature.

Module AlloyComposition

DataFile   =
C:\Users\audun\OneDrive\Desktop\Weldsim\weldsim_software\inpfiles\idb/Composition.txt   ! Input file for kinetic data

! Id   Data set

1   HYB6082Base

2   HYB6082Base

3   HYB6082Wire

4   5183a

5   5183a

EndModule

!===!

! Some variables referred to in PSD microstructure data sets

$DDL   2.0E-10 ! DistribDiffusionLength

$DR   4.0e-11 ! RcincMinBetaDouble

$Sigma1   0.03   ! Datagroup Particle/matrix interfacial energy [J/m^2]

$PreSpRadLim 1.1E-9   ! Datagroup   PrecipSphereRadLim

$PreL2R   26.0   ! Datagroup PrecipSphereRadLim

$Rc   2.7E-9   ! Datagroup Critical radius Cutting/Bypassing

$A01   9900.0   ! Parameter related to the energy barrier for nucleation [J/mol]

$DeltaGs   1.0

$A0Bd2Bp   0.0

$J0Bd2Bp   0.0

$Rminbd2bp   0.0

$RadExpbd2bp 0.0

!==!

! Particle size distribution or PSD module. Calculating particle movement changes in the material depending on the temperature history.

Module ParticleSizeDistribution

DataFile
C:\Users\audun\OneDrive\Desktop\Weldsim\weldsim_software\inpfiles\idb\PSD_micro.txt   ! Input file for kinetic data

RoomTempAgeingFromTime 3000.0

FullyNaturalAged

! Giving a cap at time 3000 for roomtemperature ageing after that point. The simulation then uses existing data on the material to calculate the state of the material after ageing at room temperature and implements that to the model.

NoUseReferenceAlloy

SimpleEqulibrium

SimpleEq2015

NoBothMgAndSiInNucleationLaw

AlternativeComposition

AlternativePrecipShape

AlternativessStrength

boostdiffusionfactor   4.0

boostdiffusionfraction   0.015

boostdiffusionretard   0.03

boostdiffusionstop   0.05

BoostDistribExponent   0.7

DistribDiffusionLength   5.0E-11

BoostModifyMeanConc

BoostMeanConcExp   0.01

AlternativeHardness

Eps_HV   0.05

Alloyhardeningconstant { 900.0*1000000/3.565620142 }

Alloyhardeningfactor   { 700.0*1000000/3.565620142 }

BetaDoublFile   =
C:\Users\audun\OneDrive\Desktop\Weldsim\weldsim_software\inpfiles\idb/age_6082_Be
taDbl_20400.szd

RefBetaDoublFile   =
C:\Users\audun\OneDrive\Desktop\Weldsim\weldsim_software\inpfiles\idb/age_6082_Be
taDbl_20400.szd

! Files containing ageing data for Alu 6082, used in this welding process.

RefPseudoNodeId   2

Subtractnumericaldiffusion

UseRepPartRadiusBetaPrime

NoBetaPrimeNuclDepOnMnConc

NumBetaPrimeNuclSites   2.0E10   ! Number density of beta prime nucleation sites
[#/m3].

TemperatureLimit   = 120.   ! Temperature limit for calc. [oC]

NclassBetaDouble   = { 220.0E-10 / &DR }   ! Number of size classes [-]

RcminBetaDouble   = 7.0E-10   ! 10.0e-10   ! Min. size of the class [m]

RcincMinBetaDouble   =   &DR   ! Min. increment [m]

RcincfacBetaDouble   =   1.0   ! Increment factor [-]

! Id   Parameters Model

! Apply full PSD model to aluminium parts. The steel does not have PSD model in this
version of the program. However, the steel is not essential in regards of the weld strength.

1 Model_jan18   1

2 Model_jan18   1

3 Model_jan18   1

4 Model_jan18   -1

5 Model_jan18   -1

RefPseudoNodeId   2

ResultNode 1

BetaDoublResultAtNode

NoBetaPrimeResultAtNode

EndModule ParticleSizeDistribution

!===!

! Module calculating the microstructural changes in the materials, depending on the temperature history and the PSD model.

Module microstructure

DataFile
C:\Users\audun\OneDrive\Desktop\Weldsim\weldsim_software\inpfiles\idb\micro.txt

!ID model data set

   1 0   7108T6 !dummy

   2 0   7108T6 !dummy

   3 0   7108T6 !dummy

   4 5   AlFeInterface

   5 0   7108T6 !dummy

EndModule   !CHANGED! <-

!==================New for Mech=========================!

! Simplified mechanical properties used for the materials in simulation.

Module MechanicalProperties

Gravity 0.0 -9.8 0.0

ZeroThermalStrainTemperature &AmbTemp

Data File=
C:\Users\audun\OneDrive\Desktop\Weldsim\weldsim_software\inpfiles\idb\MechProp.txt

!Data File =   idb\MechProp.txt

!   PATRAN   Mechanical properties

!   Id   Data set names

1   Alu6060

2   Alu6060

3   AA5183

4   DP600

5   DP600

$T4Scale   { 75.0 / 80.0 }

$T6Scale   { 190.0 / 210.0 }

PropertySet Alu6060

Density   2600.0

CoherencyTemp   620.0

Formulation   4

ElasticityType   1

EmoduleData   EmoAl_1

PoissonData   PoiAl_1

ThermalExpantype   1

ThermalExpanData   Beta_DC

PlasticityType   15

PlastConstEqTables

PlasticityData   Tab1_Scaled_6060

PropertySet AA5183

! Increased density in the added material (wire) to account for increased area after welding that is not a part of the geometry.

Density   3240   ! 2700.0

CoherencyTemp   540.0

Formulation   4

ElasticityType   1

EmoduleData   EmoAl_1

PoissonData   PoiAl_1

ThermalExpantype   1

ThermalExpanData   Beta_DC

PlasticityType   13

PlastConstEqTables

PlasticityData   AA5183

PropertySet DP600

Density   7800.0

CoherencyTemp   1450.

Formulation   4

ElasticityType   1

EmoduleData   Emo_WorkShop07

PoissonData   Poi_0.3

ThermalExpantype   1

ThermalExpanData   MortenOBetaFerrite

PlasticityType   13

PlastConstEqTables

PlasticityData   Norm_DP600

EndModule

!==================New for Mech========================!

Module MechanicalBoundaryConditions

DefaultFree

! ID   BC   Code Boundary condition data set

 5 22 [1.0E7 1.0E7]

 12 22 [1.0E7 1.0E7]

!   BID1   BID2   Code   Data

! Boundary conditions between different interfaces. Internal interfaces differ from contact interfaces.

interface 1 2 1022   [1.0E13 1.0E13]

interface 3 4 1022   [1.0E13 1.0E13]

interface 3 4 1022   [1.0E13 1.0E13]

interface 5 6 1022   [1.0E13 1.0E13]

interface 7 11 1047 ContactBetweenParts

interface 8 11 1047 ContactBetweenParts

interface 9 11 1047 ContactBetweenParts

interface 10 11 1047 ContactBetweenParts

interface 13 14   1022   [1.0E13 1.0E13]

interface 15 16   1022   [1.0E13 1.0E13]

interface 17 18   1022   [1.0E13 1.0E13]]

Inliningdatasets

DataGroup ContactBetweenParts

OffsetForce 0.0

! Displacement stiffness for contact between parts

-1.0   1.E6 ! Pa/m , or /N/m2/m

-0.00002   1.E7

-0.00001   1.E8

0.0   1.E9

0.00001   1.E10

0.00002   1.E12

! From here we define the tangential stiffness

Anotherspring   ! tangential stiffness

Zerodispforce 0.0

! Disp   Stiffness

-1.0   1.E9

0.0   1.E9

EndData

EndModule

!================New for Mech============================!

Module MechanicalResiduals

MaxPlasticIterations 2 ! 24

MaxLocalIterations   66

MinPlaStrainRate   1.0E-66

PlastIterCrit   1.0E-6

LocalIterCrit   0.0001

MaxEffIncChangeNoRelax 0.015

underrelaxationhg   0.6

! NoAccelConverg

AccelConverg

IterFirstAcc   2

IterLastAcc   15

IterIntervalAcc   3

MinStrRateAcc   1.0E-12

Par1Acc   1.5

Par2Acc   1.3

Par3Acc   2.

EndModule

!==============New for Mech============================!

Module NumericalIntegrationStress

NoMonitoractivity

NoMonitorIncompatible

NoUpdatedLagrange

NoAdjustLiquidNodeDisp

ElementTempIsMaxTemp

NoPurelyDeviatoricHGStrains

HgShearStiffness

FilletAnchorFactor   4.0E+8

FilletAnchorMinHeatRate   50.0

FilletAnchorMinTemp   470.0

liqboundarystiff   1.0E5

liqinterfacestiff   1.0E12

StoreElementMatrix

StabilizePE6TE4

StabPE6TE4Tlim 420.0

StabPE6TE4Fact 0.03

EndModule

!===!

Module GlobalEquationSolver

SetZeroBid2Id

Nozeroboundidwarn

PardisoReUse

SolverTherm   1

IccgMaxErrTherm   1.E-21

FffTherm   0.00

FillinLevelTherm   -1

MaxIterationsTherm 700 ! 300

eliminateliquiddofs

SolverMech 2

FillinLevelMech = 2

MaxIterationsMech = 8000

IccgMaxErrMech = 1.E-16

FffMech = 0.01

Iclamp = 0

FixFilletSingularity

EndModule

!==!

Module Refinement

! Refinement of the mesh in the welding sone to insure good element quality and even element size throughout the weld.

  NoMeshExport

  RefinementLevel = 1

  AnisotropicRefinement

  ElementMaxDimensions   0.006   0.006   0.006   0.006   0.006

  ElementMinDimensions   0.003   0.003   0.003   0.003   0.003

  TimeEndRefining 0.4

  RefinementCriterion =   ElementShape

  MinTimeBetweenRefinements   0.5

! TempDiffisoLimit1   =   9000.

! MinTempChange4Refinement 40.0

! welddistrefzone1   0.020

! EnforcedRefBox 0.125 0.175 -0.001 0.03 -0.01 0.01

  RefinementBox 0.090 0.110 -0.005 0.03 -1.01 1.01

  NoCoarsening

  FirstRefinementRadius 0.0

  FirstRefinementMaxLevel 0

EndModule

!===!