



University of Padua

Department of Industrial Engineering

Master's Degree Course in Mechanical Engineering

Characterization of AA6082-T6 Aluminium Alloy and S355 Steel Welding Achieved with the Hybrid Metal Extrusion & Bonding (HYB) Process

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Abstract

The Hybrid Metal Extrusion & Bonding (HYB) is recent cold-welding technology used for welding aluminium (Al) plates. The process makes a strong junction by squeezing in an extruded aluminium wire used as filler material (FM) between two plates of base material. This process is applied now for dissimilar welding. The scope of this work is the mechanical characterization of a weldments of dissimilar materials: a AA6082-T6 aluminium alloy rolled plate, and a structural S355 steel rolled plate. A welding between these two commons material has a considerable industrial interesting where low weight and low cost are required. The high amount of knowledge about the two metals individually, makes a joint of them very attractive. But the welding is also critical because the two metals have different properties: in this work it's shown the high level of this new technology trough remarkable mechanical results. The strength of the joint is high compared with the base material and the intermetallic layers are extremely thin because of the low temperature process. HYB method is developing and seems to have a great future.

In this thesis the experimental analyses are hardness testing and tensile testing. The samples were selected from different regions of the welded plate to analyse differences on the position. Moreover, optical microstructure analysis of the weld and scanning electron microscope (SEM) examination of fracture surfaces and bonding area have been carried out.

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Abbreviations and symbols

Al	Aluminium
BM	Base material
CEW	Coextrusion welding
CM	Confocal microscope
CMT	Cold metal transfer
CW	Cold welding
CPW	Cold pressure welding
DCI	Digital image correlation
DFW	Diffusion welding
EXW	Explosion welding
Fe	Iron
FM	Filler material
FOW	Forge welding
FRW	Friction welding
FSW	Friction stir welding
FSSW	Friction stir spot welding
GMAW	Gas metal arc welding
GTAW	Gas tungsten arc welding
HAZ	Heat affected zone
HPW	Hot pressure welding
HYB	Hybrid metal extrusion & bonding
HV	Hardness Vickers
IMC	Intermetallic compound

IMP	Intermetallic phase
MAG	Metal-arc active gas
MIG	Metal-arc inert gas
MPW	Magnetic pulse welding
OM	Optical microscope
ROW	Roll welding
SEM	Scanning electron microscope
SPCC	Steel plate cold commercial
T4	Naturally aged condition
T6	Peak-aged condition
TIG	Tungsten inert gas
TMAZ	Thermo-mechanical affected zone
USW	Ultrasonic welding
UTS	Ultimate tensile strength

1 Introduction

1.1 Background

Nowadays there are many studies about innovative metallic and advanced ceramics materials but steel is even now the most important. During a lesson Professor G.M. Paolucci said “The steel, for the Mechanical Engineer, is like the oxygen for the living creatures”. The steel has the problem that its specific weight is higher than other materials so a way to build constructions with steel and different and lighter metallic materials is important.

Reducing CO₂ emissions is essential for cost decreasing strategies and many industries spend large amount of money on design products with this aim. One obvious solution is the weight reduction, and lighter materials help to achieve this goal. Among the widely used metallic material there are aluminium and steel and combine them together it's possible to have lighter structures with the correct resistance and stiffness at a reasonable cost.

There are many aluminium alloys available for commercial use, with different properties that depend on the alloying elements. For instance, the Al-Mg-Si alloys (6xxx series) has good formability, machinability as well as the ability to be fusion welded. Among the steels the S355 is structural steel very common with great weldability and machinability. These two metals are good candidates to be joined in a large industrial scale to combine the lightweight and the high thermal and electrical conductivities of aluminium with the low cost and the high structural strength of steel.

These materials need a good junction process to enhance their properties and the welding processes are the best choice compared to other joining methods like fastening or adhesives. On the other hand, welding process change the microstructure of the base material near the welded zone. The first reason is due to high temperature generated during the process, common in classical types of welding. This produce hidden stressed areas that can be dangerous for the life of the products. The second reason is due to chemical incompatibilities like intermetallics and oxides growth that affect in particular the dissimilar welding. To prevent this is important to keep low temperature gradients to achieve efficient welding. Last decades have seen the development of new welding techniques that need lower temperatures called cold welding processes.

Cold welding processes, like cold pressure welding, friction stir welding friction welding, explosion welding, and others, can obtain high quality metallurgical joining without

melting base materials with incredible results, better than old methods. Among these new methods there is the Hybrid Metal Extrusion & Bonding HYB, developed by Professor Øystein Grong, Engineers Ulf Roar Aakenes and Tor Austigard, in collaboration with the Norwegian University for Science and Technology and the support of Statoil. This process is tested with AA6082 Aluminium plates and also for dissimilar joining between S355 steel plates and AA6082 Aluminium plates. The process uses a filler material and plastic deformation to create a solid state joints at lower temperatures than usual processes and with good strength and less cracking and corrosion problems.

1.2 Objectives

The HYB process is not widespread in literature. The aim of the present report is mechanical characterization of a HYB joining between S355 steel and AA6082-T6 aluminium.

1.3 Scope

The work present hardness and tensile tests with attention to the microstructure. The tests were carried out at different location of the sample analysed, at the beginning, in the middle and at the end, to search differences due to the position. In addition, the microstructural features of the joint were studied by optical microscopy. After the tensile test the fracture surfaces were analysed in a scanning electron microscope (SEM). All the mechanical testing is carried out at room temperature.

2 Theory

This big topic can be introduced by answering questions like how materials can interact together and be joined again, why some welding are stronger than others, how a good joining process can be developed. But first, why aluminium and steel? As said before, reducing weight in transport industries as well as in other industrial fields is one of the most critical aspects affecting emissions [1], forcing technology to adapt and evolve itself towards better environmental quality standards. The high strength, stiffness, and resilience of steel [2], in combination with low weight, corrosion resistance and good weldability of aluminium alloys [3], make this coupling so important to engineering applications. The European Aluminium Association stated, in its Aluminium Automotive Manual from 2015 [4] concerning automotive engineering, that aluminium and steel joining would be the objective of the next years. Other possible outlets are land and sea transport industries as well as metallic structures applications, oil and piping engineering and some special civil buildings.

2.1 The metallic bond

Metals tend to have high melting point and boiling points suggesting strong bonds between the atoms. Metals are characterized by a specific type of bonding, the metallic bond. This is a strong intermolecular bond, like the ionic and covalent bond. Most metals have very few electrons in their outermost energy shells, and some have vacant outer electron orbitals. What this means for the metal is that its valence electrons are decentralized and free to move. **The valence electrons are shared**, the electrons wander around and aren't transferred or shared. It's more of a communal thing where they belong to all the metal atoms around them. When metals are next to each other, the valence electrons don't just stay on their own atom; they roam around the whole metal complex. They float free as though floating through a sea of electrons therefore it is called the electron sea model. **Figure 2.1 shows the situation.** Each metal atom allows its electrons to roam freely, so these atoms become positively charged cations. These cations are surrounded by a “sea” of negatively charged electrons. The electrons movements produce the typical thermal and electrical conductivity of metals.

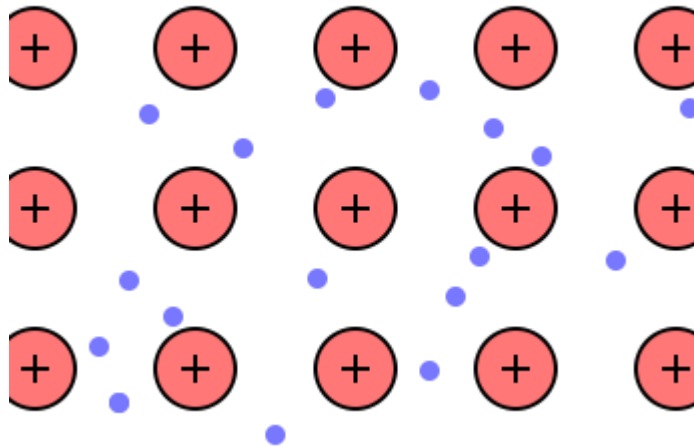


Figure 2.1. Metallic bonding. In red metallic cations, in blue electrons.

This metallic bond enables atoms to create three types of structure: face-centered cubic (FCC), body-centered cubic (BCC), or hexagonal close packed (HCP). Depending on atoms distribution metals have their properties of strength, ductility, thermal and electrical conductivity.

Inside the lattice it's easy to find impurities that change properties as ductility: the presence of impurities reduces this property. Theoretically two similar metals could be attached together by simply forcing them against each other and applying the right pressure. If the surfaces are perfectly flat and the distance between atoms is short, the metallic bond should be created and the electrons shared. But the reality shows that is impossible to have perfect flat surfaces and oxide layers are always present and don't react like the BM.

Dissimilar welding, has another enemy that from the interaction of different atoms: the formation of intermetallic compounds (IMCs). The characteristics of the intermetallics, such as hardness, thermal conductivity, potential for galvanic corrosion, melting temperature are very different from those of the base materials. Thus, the interface between two different metals is the weak part of the joint.

It's really hard to prevent the formation of IMCs because they come from natural processes. The diffusion produces the movement of atoms and in metals the prese, mainly as interstitial defects and vacancies promote the process. Atoms move mostly as interstitial defects and change the properties of the material. The high temperatures helps the diffusion so in fusion welding has a large impact and in this way the cold bonding is better.

2.2 Aluminium and steel phases

The oxides cover the surfaces of the metals. Structural steel has very low carbon content and has different oxides. Typically, iron oxides are porous, and they grow slowly. Steel can be shielded to avoid oxidation after any operation. Sometimes, it is only needed to clean surfaces before the process. Aluminium has a natural oxide called Alumina that grows fast on clear Al surfaces. When a new Al surface is exposed, for example after fractures, a process called passivation immediately cover the new exposed metal. This is a shielding process that creates a high-density layer, particularly hard to penetrate, that protects bulk material and gives aluminium its anti-corrosive property. The oxide provides an optimal tendency against oxidation of all the material, that is different from the response of common steel. The passivation is a problem for the bonding, since alumina must be scratched away to promote metallic bonding between Al atoms. But the process is fast so it's not easy to maintain a de-oxydate surface.

The Fe-Al equilibrium phase diagram is shown in Figure 2.2. The system show the most common intermetallic compounds: Fe_3Al , FeAl , FeAl_2 , Fe_2Al_3 , Fe_2Al_5 and FeAl_3 . Table 2.1 indicates some important characteristics of the IMPs. The aluminium and iron phase diagram shows all the different IMCs possible. The higher is the temperature, the bigger will be the probability to have IMCs formation.

In dissimilar welding between aluminium and steel, the two metals react depending on welding parameters like temperature, pressure, time, and atmosphere influencing diffusion ratio. All this factor affected the formation of different IMCs. Different IMCs have different mechanical properties: some of them are ductile and other are really hard.

There are three main thermodynamical factors that produce the IMC: the mobility of the alloying elements during the welding processes; the chemical potential of elements; the nucleation of the phases at the beginning of the interdiffusion.

During thermal joining of dissimilar material the temperatures are high and the formation of IMPs must be considered. Some new phases can grow on the bonding that cause an embrittlement of the joining zone. To have a good weldment IMCs must be limited to a minimum size. The main parameters are the limitation of the overall heat input and the reduction of melting pool dimensions.

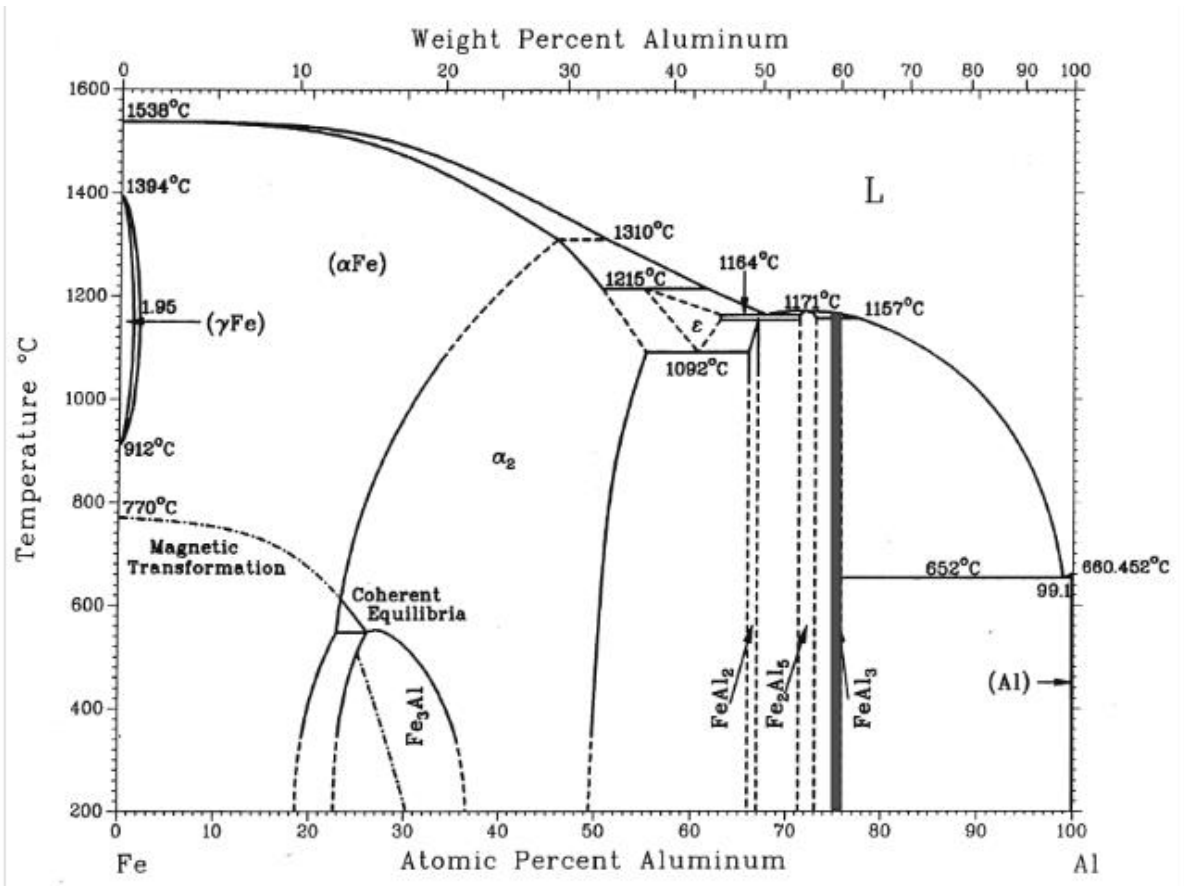


Figure 2.2. Phase diagram of aluminium and iron

Table 2.1. The most expected IMCs between aluminium and iron [8-10].

Phases	Crystal structure	Stability range (at.%)	Vickers Hardness (9.8N)
Fe solid solution	BCC	0-45	not investigated
γ-Fe	FCC	0-1.3	not investigated
FeAl	BCC (Order)	23-55	470 ^[3] (491 – 667) ^[4]
Fe ₃ Al	DO3	23-34	330 ^[3] (344 – 368) ^[4]
Fe ₂ Al ₃	Cubic (complex)	58-65	not investigated
FeAl ₂	Triclinic	66-66.9	unknown ^[3] (1058 – 1070) ^[4]
Fe ₂ Al ₅	Orthorhombic	70-73	1013 ^[3] (1000 – 1158) ^[4]
FeAl ₃	Monoclinic	74.5-76.5	892 ^[3] (772 – 1017) ^[4]
Al solid solution	FCC	99.998-100	not investigated

2.3 Welding technologies

Dissimilar material welding started around the 1950s. At the beginning, several attempts were made to achieve dissimilar welding through different techniques and using different heat sources but the fusion welding was the most used. For the high temperatures reaches the results weren't good because of the formation of IMCs. The technological developments gave more governable process and possibility to control the heat transferred to the metal work pieces. If the heat absorbed is high the zone with IMCs is larger. So a key role has the dissipation of the heat. There are several different welding techniques nowadays but not all are good for dissimilar welding.

A first difference among the welding methods is the temperature of the process: for $T > T_{\text{melt}}$ there is the fusion of base material; for $T < T_{\text{melt}}$ there isn't the fusion of the base material. The technologies interesting for our scope are without fusion of base material and are called Solid state welding.

2.4 Fusion welding

Fusion welding. Processes use heat to melt the base metals. In many fusion welding operations, a filler metal is added to the molten pool to facilitate the process and provide bulk and strength to the welded joint. A short description of the most important is presented.

- Gas welding is a welding process that melts and joints metals by heating them with a flame caused by a reaction of fuel gas and oxygen. The most commonly used method is Oxyacetylene welding, due to its high flame temperature.
- Arc welding is a type of fusion welding that uses a welding power supply to create an electric arc between an electrode and the base material to melt the metals at the welding point. They can use either direct (DC) or alternating (AC) current, and consumable or non-consumable electrodes. Arc welding processes may be manual, semi-automatic, or fully automated. First developed in the late part of the 19th century, arc welding became commercially important in ship building during the Second World War. Today it remains an important process for the fabrication of steel structures and vehicles
- High Energy Beam Welding The high-energy beam welding is a fusion welding process that utilizing a heat source, which is capable of proving extremely high-

power density, weld input levels. The density of the energy available from a heat source for welding has more important over the absolute source energy. There are two main processes of high-energy beam welding: the Electron Beam Welding (EBW) and the Laser Beam Welding (LBW).

2.4.1 Solid state welding

The fusion welding generates too much heat, even if in narrowed space, so a clever solution was to change the approach. This settled down the road towards cold welding processes. In fact, solid state processes, figure 1.7, are particular techniques where the temperature does not melt base materials (BM), so the name “cold”. Metals being joined almost retain their previous properties thanks to the absence of melted nugget and consequently of the HAZ effect. That can drastically reduce residual stresses, property decay, and IMCs formation issues.

Solid-state welding is defined as a joining process without any liquid or vapor phase, with the use of pressure, and behind T_{melt} . Solid-state welding is done over a wide range of pressure and temperature, with appreciable deformation and solid-state diffusion. In solid-state welding, the cohesive forces between metal atoms are utilized. Other forces, for example, van der Waals forces, are expected to be of lesser importance. Metals being joined almost retain their previous properties thanks to the absence of melted nugget and consequently of the HAZ effect. That can drastically reduce residual stresses, property decay, and IMCs formation issues. Some techniques are more spread than others. Summarized below are some studies achieved on the most known solid-state processes, which more or less always present IMCs formation.

- Magnetic pulse welding (MPW) is a high speed joining process using electromagnetic forces, because of clean and multi-material operation has a wide range of possibilities. It acts accelerating metal pieces against each other. The impact will create the coalescence between dissimilar metals. It presents some of the limitations of USW applications like shape and thickness; in addition, care must be used selecting the right distance between the surfaces to be joined.
- Ultrasonic welding (USW) breaks oxide layers using the mechanical action of high frequency vibrations. In this case, it is not necessary to have clean surfaces; however, thick

and complicated shapes should be avoided. Good results were achieved in a butt joining configuration analysis.

- Roll welding (ROW) is very common in producing bimetallic foils. It requires very clean surfaces before the treatment. The two metals are simply forced together to be rolled, promoting joining under many variables. Often metals are preheated, but sometimes, failures, due to brittle layer between aluminium and steel, can still happen.
- Explosion welding (EXW) is a technique that can give really good joint quality. It works like MPW by accelerating an upper metal piece, usually sheets, towards the lower one, thanks to an explosive material. Therefore, the impact speed compared to that in MPW is much higher. It results in a superplastic deformation between metals and in a supersonic ejection of oxides from contact surfaces as well. It is largely used to provide bimetallic clad products to facilitate union in big structures
- Diffusion welding (DFW) has good results, but since the need of long coalescence time is required, high productivity is not possible. The DFW process needs the application of pressure and temperature to an interface for a prescribed period of time. High temperature is also required to raise diffusivity and lower process time, but distortion is the negative side of the medal. In the same way of ROW, care on surfaces cleanness must be taken to efficiently activate the diffusion process.
- Cold pressure welding (CPW) is a bonding process where metal wires are joined by pushing their terminals against each other.
- Friction welding (FRW), friction stir welding (FSW) and friction stir spot welding (FSSW) are all based on friction as the source of heat. Mechanical energy, stored in a flywheel or generated by a rotating spindle as well as an alternate movement, is converted into friction and deformation. Thus, once the relative movement of the pieces is stopped, plasticized metals achieve the metal bond. Fine calculations make possible to give enough energy only to promote the joint. This joining technique is energy efficient, environment friendly, and versatile. In particular, it can be used to join high-strength aerospace aluminum alloys and other metallic alloys that are hard to weld by conventional fusion welding.

2.5 Hybrid Metal & Extrusion Bonding process

2.5.1 Principles of the technology

An important principle of the HYB process is the continuous extrusion. Continuous extrusion is a widely forming process used in recent days, and it has a great progress. It's used for deforming many non-ferrous metals especially aluminum and copper as well as their alloys. Continuous extrusion has some similarities to indirect extrusion, where the die is pushed into the billet in a closed container. In continuous extrusion, there is a rotating extrusion wheel provided with a slot for metal feeding, a stationary shoe with an abutment and a die. Since the slot is moving, while the shoe is kept stationary, there will be a net frictional force setup on two of the four contacting sides. To obtain extrusion in this case, a stationary abutment fixed to the shoe punctures the slot. This leads to pressure build-up ahead of the abutment and eventually forces the material to flow plastically out of the die. [34]

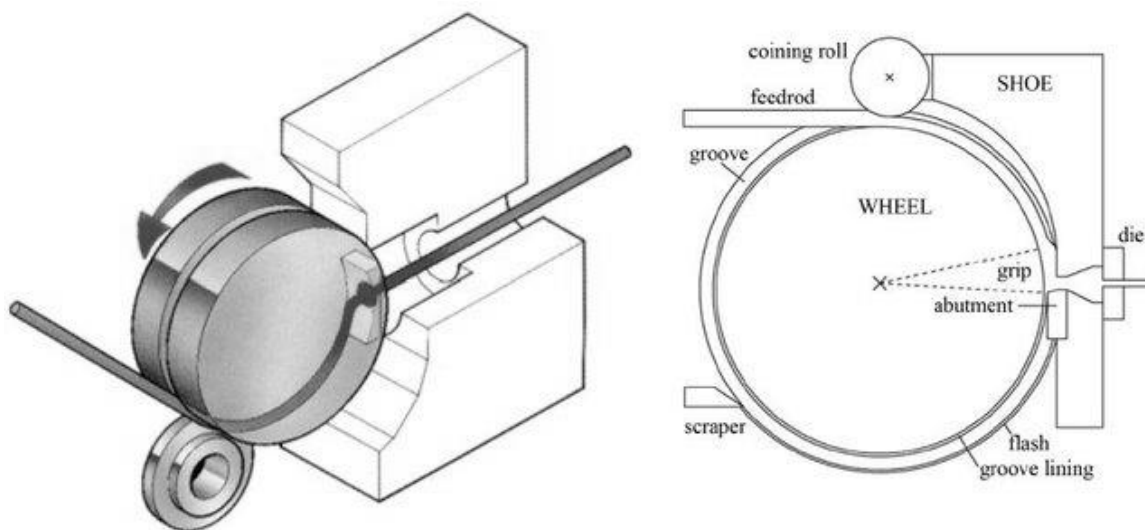


Figure 2.3. Continuous extrusion technology (L. Song, Y. Yuan, Z. Yin, "Microstructural evolution in Cu-Mg alloy processed by conform")

2.5.2 The HYB process

The hybrid metal extrusion and bonding (HYB) process is a new solid-state joining technique developed at the beginning for aluminum alloys. It uses a filler material and a plastic deformation to create sound joints at operating temperatures below 400 °C. This new process, developed by Professor Øystein Grong, Engineers Ulf Roar Aakenes and Tor Austigard, is a revolutionary way to achieve bonding without melting base material, for this reason it belongs to the cold welding processes.

The extrusion is the process where a metal billet with a cross section is forced to flow plastically through a die of the desired cross section under high pressure. The pressure needed for the metals is extremely high, so most metals are extruded under hot conditions, which reduces the deformation resistance. However, cold extrusion is possible for many metals.

The theory of the process is extruded by forcing a plasticised Al (AA6082-T4) wire between two Al plates (AA6082-T6) in a butt joint configuration as is shown on Figure 2.3. The bonding is achieved by scratching and subsequently restoring the lattice action of the FM. The wire pass through a spindle extruder and is pushed on the plates and the FM is submitted to a work hardening process that increases its hardness enough to scrape a thin layer of the BM and overtake the sufficient pressure to promote the joint. A steel scraper reshape a V-groove to have oxide-free surfaces just before the aluminium injection. The process is performed at room temperature. The temperature generated is low and the heat generated belongs only to the strain work inside the spindle extruder. In the test two plates of 4mm 6082-T6 Al alloy were used with a 1.2 mm diameter AA6082-T4 wire.

The HYB PinPoint extruder is built around the rotating drive pin which is provided with open dies at the lower conical end, as illustrated in Figure 2.31. The pin design is customized to the specific joining situation, depending both on the base plate and the groove geometries. In the drawing shown below the pin is designed for butt joining of plates.

A schematic illustration of the main components in the HYB PinPoint extruder is shown in Figure 2.32. The pin, together with the spindle tip forms a slot, where the filler material (aluminium wire) is feed into the slot from the outside. The aluminium wire is set in motion by the frictional grip imposed by the slot walls and kept in place by a stationary steel housing sealing-off the lower end of the pin. The aluminium wire is then forced to flow

against the abutment blocking the slot and subsequently, due to the pressure built up, continuously extruded through the die openings in the lower end of the pin.

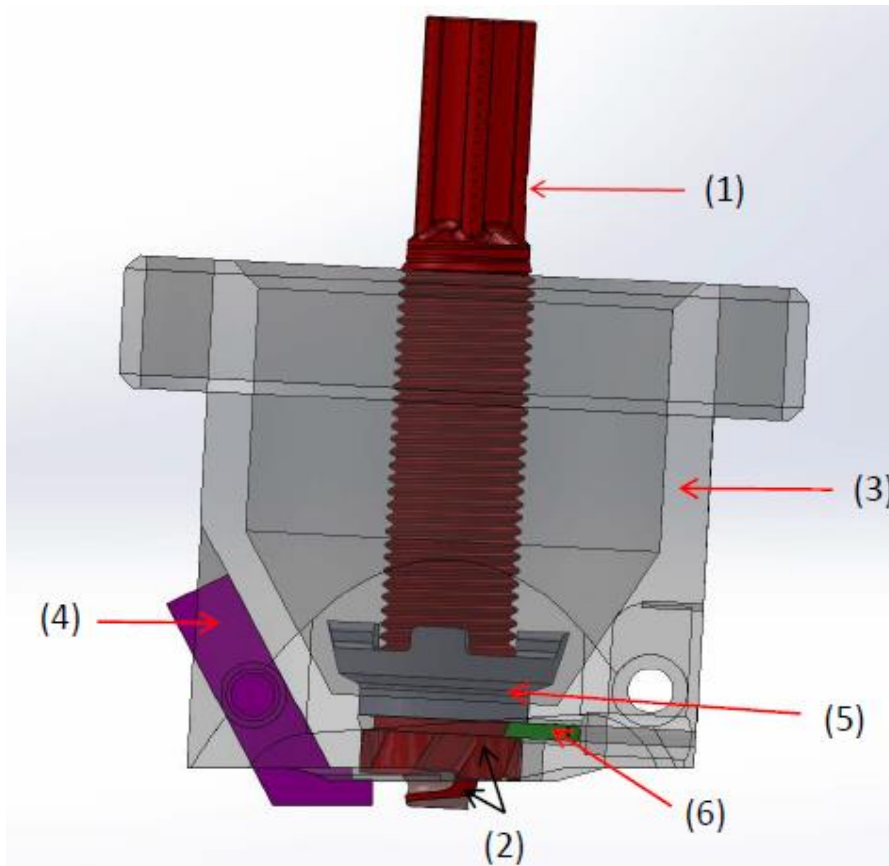


Figure 2.4. Illustration of the main components in the HYB Pin Point Extruder head; (Ø.Grong, Personal Communication)

1. inner rotating drive spindle
2. dies
3. stationary steel housing
4. replaceable skirt
5. replaceable rotating spindle tip
6. stationary abutment



7.

Figure 1.5 Conical pin used for HYB butt joining of plates; (Ø.Grong, Personal Communication)

The plates are separated from each other, so they form a groove. The plates are covered of oxide. When the extruder head is clamped to the base metal plates, the pin will enter the groove. The pin is slightly larger than the groove, which causes contact between the sidewalls of the groove and the pin.

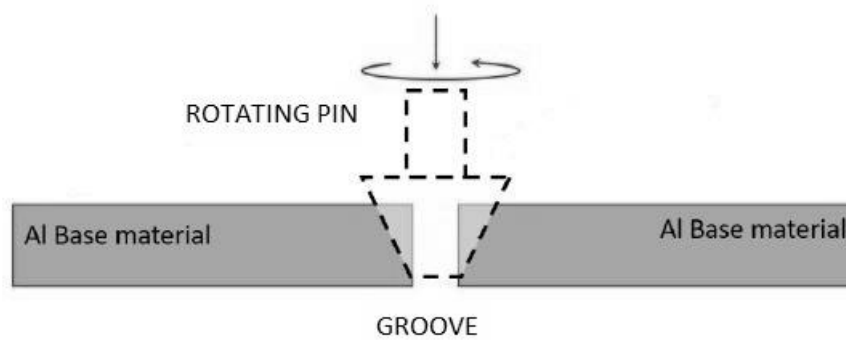


Fig 2.6. Rotating pin and its location in the groove during HYB butt welding of plates.

Two processes cooperate during the welding operation: the first one is the filling action of the extruded material, which scrape off the oxide layer, fully fill up the void between the plates, and deform the Al BM by shear stresses; the second is the action of the rotating spindle tool that work by mixing the FM with Al taken from the butt plate. This remove the oxides and promotes the surface contacts virgin BM. From the top of the plate is clear the path left from the spindle on the FM. In the transversal view is visible the flash on the top and the root shape on the bottom of the joint.

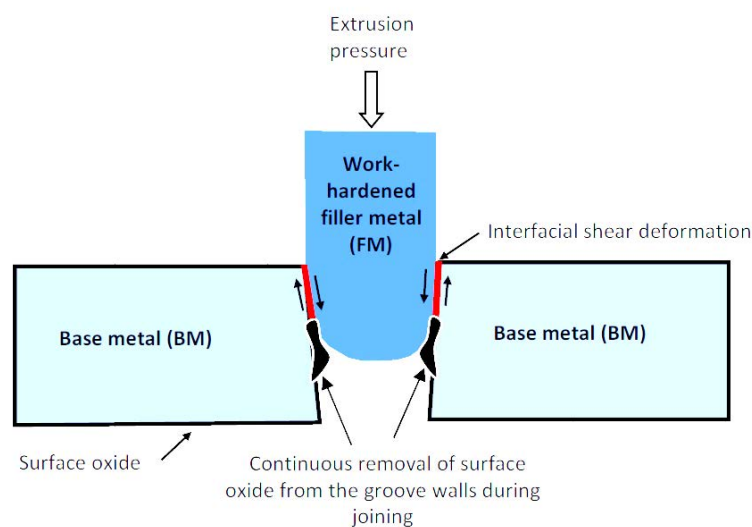


Figure 2.7. HYB configuration used for similar Al-Al welding .

As the pin rotates and travels along the joint line, the oxide layer on the sidewalls (together with some of the base material) will be dragged around by the motion and mixed with the filler metal. Metallic bonding between the sidewalls and filler metal is mainly obtained by the combined action of oxide dispersion and shear deformation, while bonding in the bottom region mainly occurs as a result of surface expansion and pressure. A cross sectional view of the material flow pattern during HYB butt welding of plates is shown in Figure. 2.8.

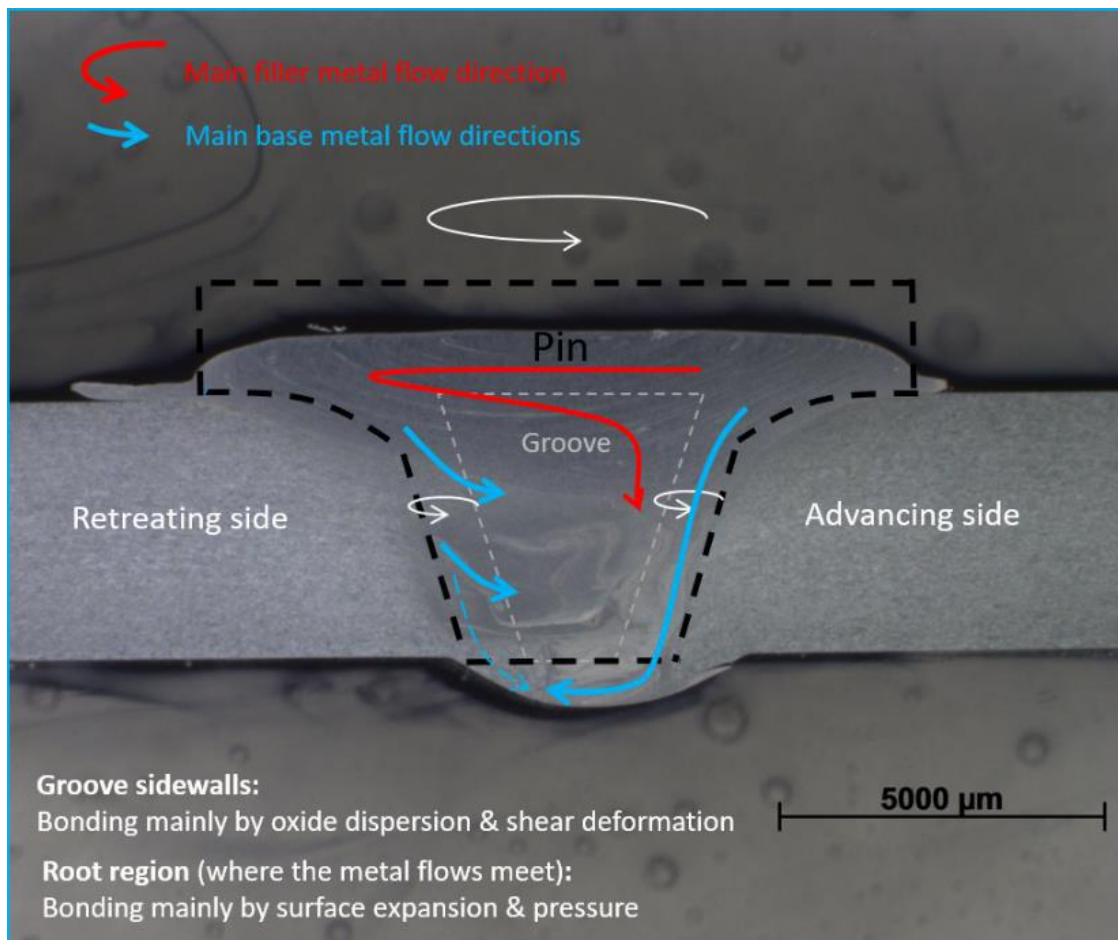


Fig.2.8 Illustration of material flow pattern during HYB butt welding of plates (Ø. Grong 2017)



Figure 2.9. Experimental setup of Al-Al HYB configuration: HYB spindle extruder (2), steel fixture (3), aluminium plates to be welded (6).

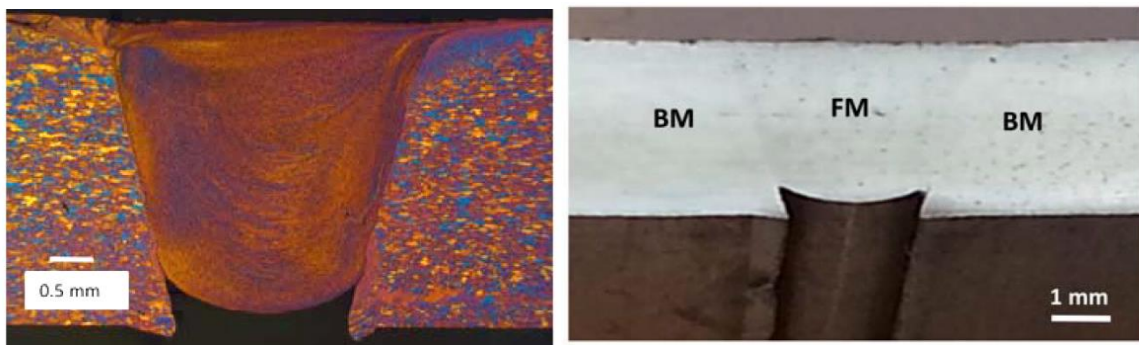


Figure 2.10. Optical macrograph of the joint cross section .

2.5.3 HYB in dissimilar welding

The technology gave good results with Al-Al so the dissimilar joining has been considered as possible. For industrial application it would be perfect to have a machine that weld different plates only changing few parameters or few parts. The answer is changing the spindle and its mount. But the important aim of the process is to be more efficient compared with alternative process and produce better weldments than other cold process competitors. The new process requires less amount of energy than that in other processes, by decreasing temperatures.

With a well designed spindle extruder (PinPoint spindle) for the specific use the dissimilar joint give good results. For the welding procedure, the aluminium and steel butt plates are

fixed leaving a gap between them. The butt surface of the steel plate need to be bevelled and fixed leaving 2 mm of space from the centre of the welding, while the aluminium plate presents a vertical surface. The shape of the steel part is important because the spindle don't have to touch the steel. The spindle extruder has a specific shape capable of squeezing plasticized aluminium in the gap between the plates while moving the material close to it. During the operation the tool operates a strain work on the aluminium side that is mixed with the filler material.

Two processes cooperate during the welding operation: the first one is the filling action of the extruded material, which scrape off the oxide layer, fully fill up the void between the plates, and deform the Al BM by shear stresses; the second is the action of the rotating spindle tool that work by mixing the FM with Al taken from the butt plate. This remove the oxides and promotes the surface contacts virgin BM. From the top of the plate is clear the path left from the spindle on the FM. In the transversal view is visible the flash on the top and the root shape on the bottom of the joint. Instead, the steel part is untouched and is clear a straight line of separation.

The best value of this process is the low temperature during the process. No preheating systems are needed and the temperature does not exceed 400°C degrees, leaving the Al BM with a barely HAZ, better called thermo-mechanical affected zone (TMAZ).

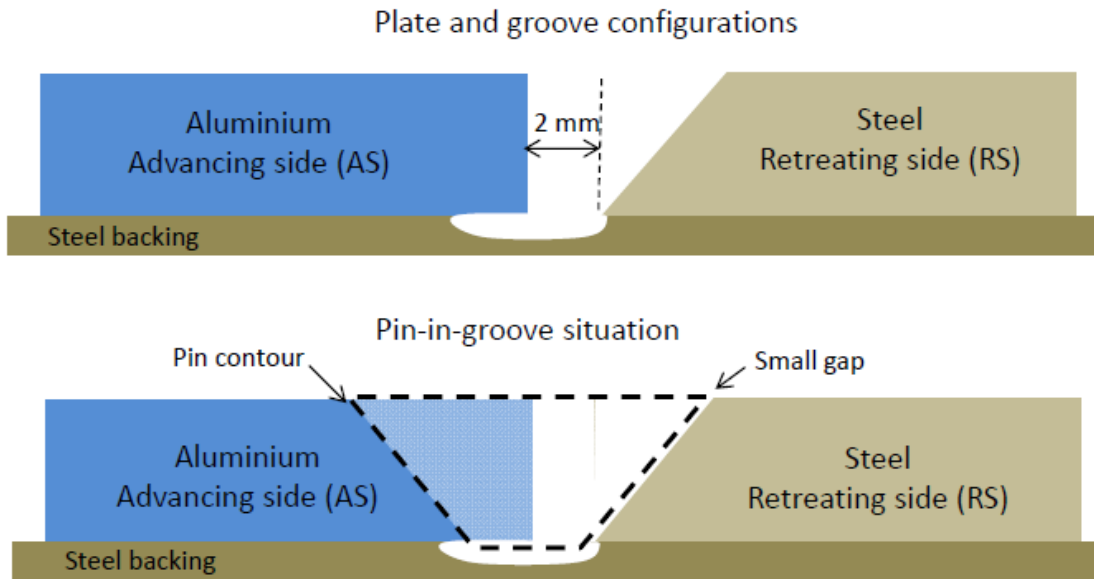


Figure 2.11. HYB on dissimilar welding, first attempt; Ø.Grong, Personal Communication

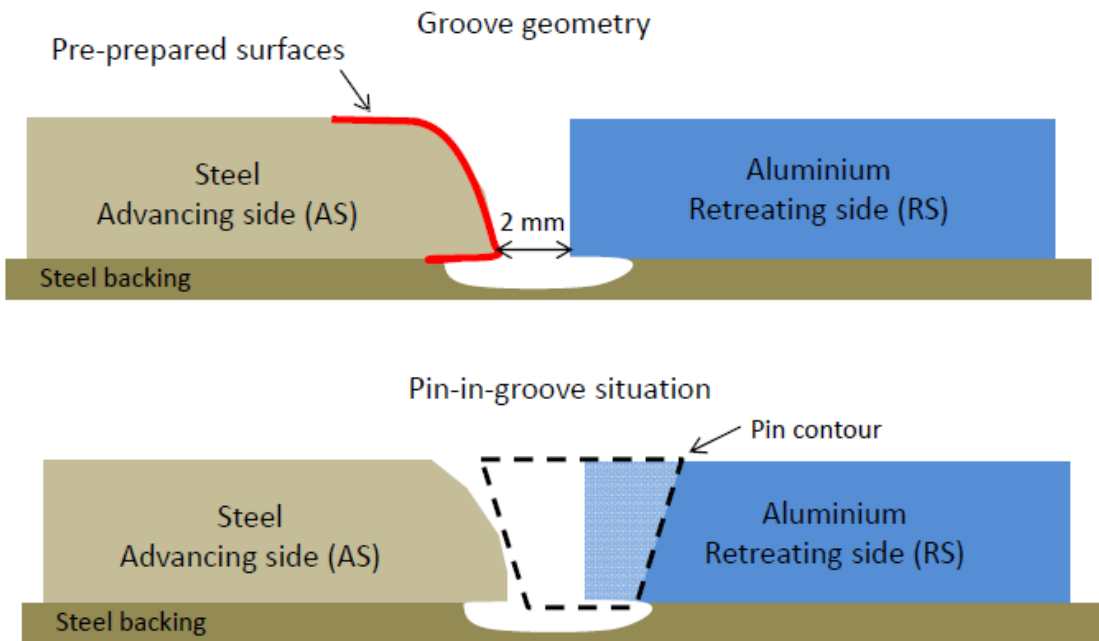


Figure 2.12 HYB on dissimilar welding, last configuration; Ø.Grong, Personal Communication

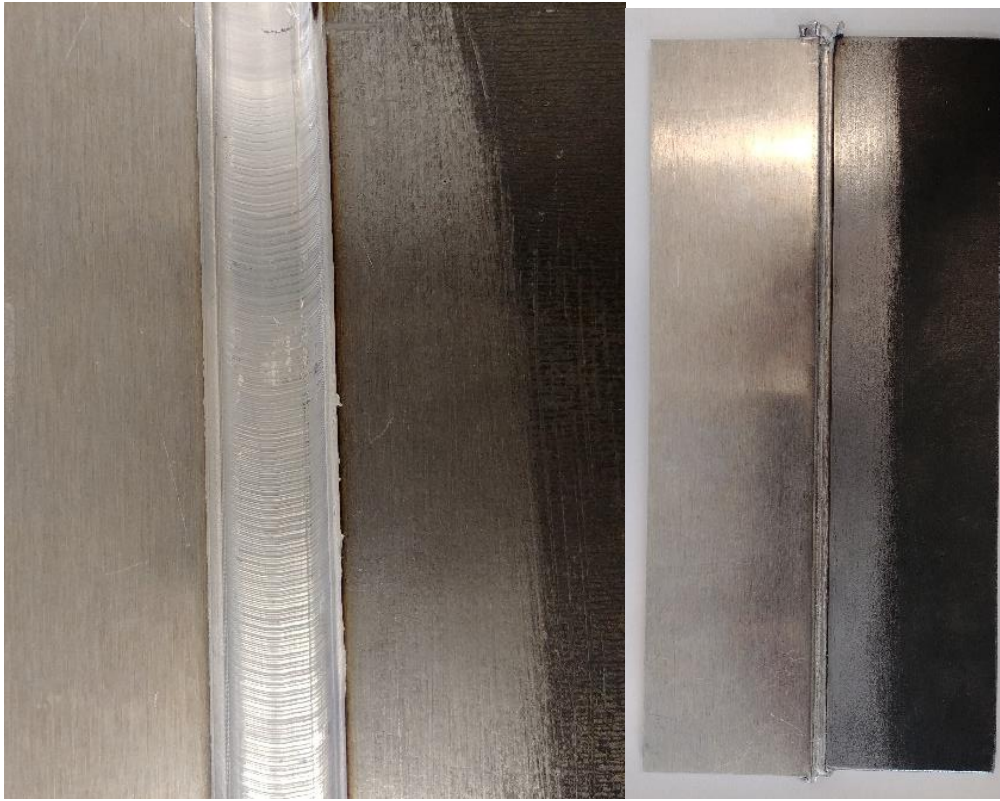


Figure 2.13. HYB dissimilar welded plates On the right the bottom of a plate. On the left a detail of the filler material. Aluminium on left side, steel on the right side.



Figure 2.14. HYB dissimilar, trasversal view of a specimen. Aluminium on left side, steel on the right side.

3 Experimental part

3.1 Materials

The welding sample analysed in this work is a plate of rolled aluminium alloy AA6082-T6 and structural rolled steel S355. The plate dimensions are: length 240 mm; width 120mm; thickness 4 mm. The plates were bought from an external supplier.

Figures 3.1 and 3.2 show the plate used for this work. The darker side is the steel and the lighter is the aluminium. At the center it's visible the filler material.

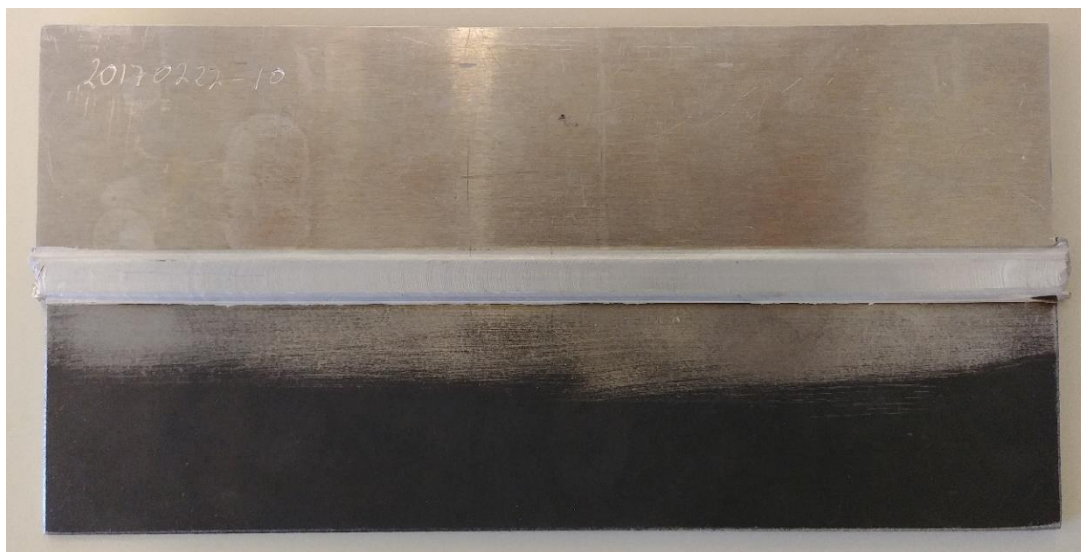


Figure 3.1 Welded plate, upper side

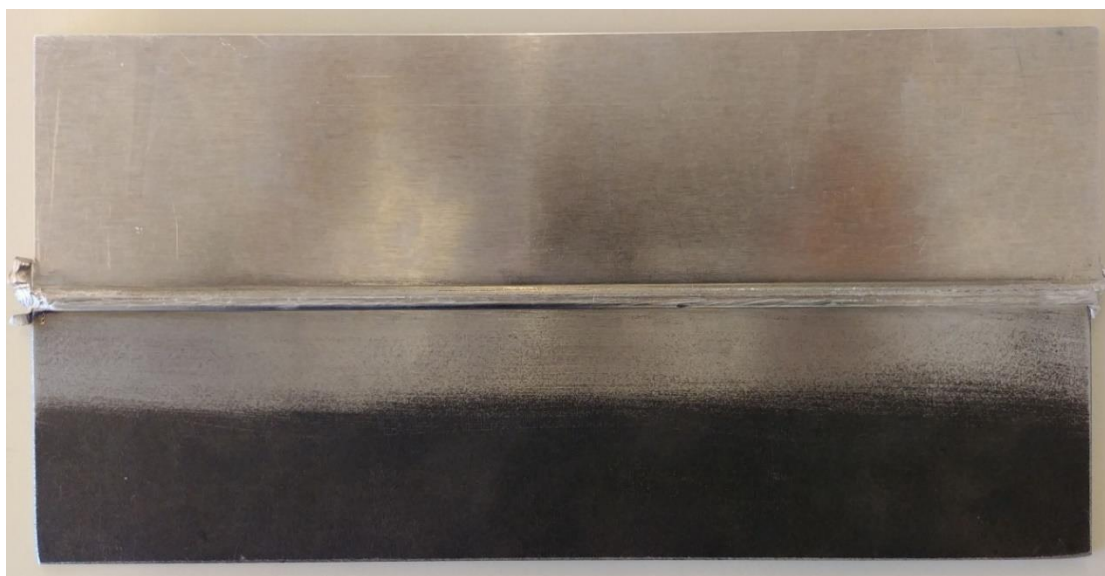


Figure 3.2. Welded plate, down side

3.1.1 Steel base material

The steel S355 is a non-alloy European standard (EN 10025-2) structural steel, most commonly used after S235 where more strength is needed. It has great weldability and machinability. The chemical composition of the steel base metal is shown in Table 3.1.

Table 3.1. Chemical compositions and mechanical data of the steel.

Alloy	Wt%	C	Mn	P	S	Si	YS (MPa)
S355 Base	max	0,23	1,60	0,05	0,05	0,05	355

3.1.2 Aluminium base material

The aluminium base material is a 6082 alloy, received in the T6 tempered condition. As a 6xxx Aluminum-Magnesium-Silicon alloy the typical characteristics are: medium strength; good formability, machinability and weldability; good corrosion resistant; heat treatable. The chemical composition of the aluminium base metal is shown in Table 3.2.

Table 3.1. Chemical compositions and mechanical data of the aluminium.

Alloy	Wt%	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	YS (MPa)	UTS (Mpa)
AA6082	Min	0,7	-	-	0,4	0,6	-	-	-	273	329
Base	Max	1,3	0,5	0,1	1,0	1,2	0,25	0,20	0,10	277	335

3.1.3 Filler material

The filler material used for welding was a 1.2 mm diameter wire of the AA6082 in T4 aged condition. This wire is produced by HyBond AS. The wire was obtained from a DC cast billet provided by Hydro Aluminium, which then was homogenized, hot extruded, cold drawn and shaved down to the final dimension. The chemical composition is shown in Table 3.3. The applied homogenization conditions are shown in Table 3.4. A detail of the filler material from the welded plate is on the figure 3.3.

Table 3.3. Chemical compositions and mechanical data of the aluminium filler material.

Alloy	Wt%	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	YS (MPa)	UTS (Mpa)
AA6082 Filler		1,11	0,2	0,002	0,51	0,61	0,14	-	0,043	-	-

Table 3.4. Homogenization condition AA6082 DC cast billets

Heat rate (°C/h)	Holding temp. (°C)	Holding time (h)	Cooling rate (°CH)
200	540	2.25	300



Figure 3.3 Filler material detail

3.2 Joining conditions

HyBond AS made a single-pass butt joining of the plates using an I-groove with 3 mm root opening and the filler wire. CO₂-gass was used for cooling. Welding parameters are shown in Table 3.5. The gross heat input (following cooling) was approximately 0.51 kJ/mm .

Table 3.4. Homogenization condition AA6082 DC cast billets

Pin rotation (RPM)	Travel speed (mm/s)	CO ₂ gas flow rate (g/min)	Wire feed rate (mm/s)
400	6	160	142

The fig. 3.4 shows the temperatures of the extruder and of the die. The temperature increase during the process and reach a maximum of approximately 430°C that is allow value.

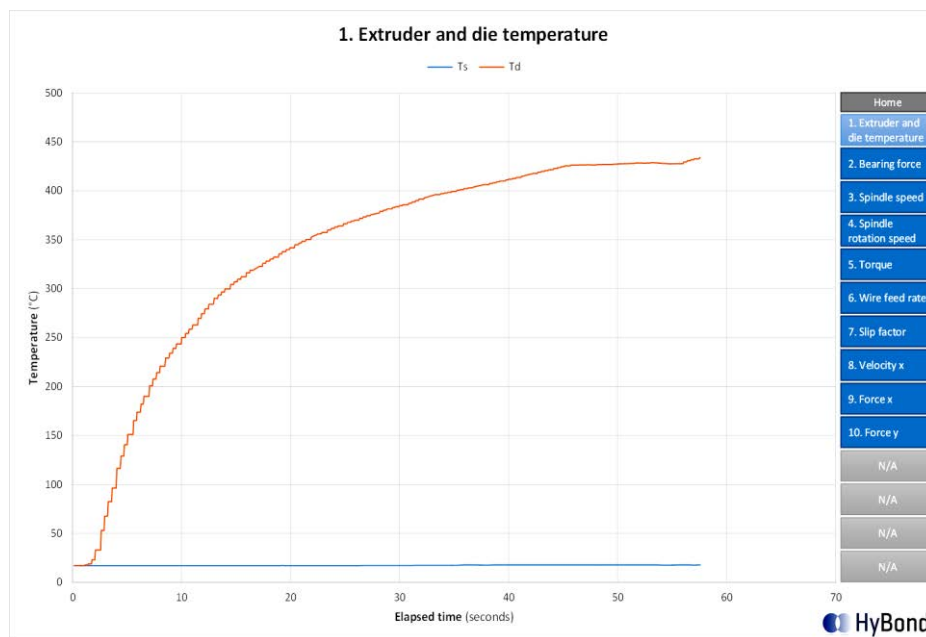


Figure 3.4. Teperatures during the process

3.3 Samples classification and preparation

3.3.1 Samples sectioning and classification

Samples were obtained by cutting, perpendicular to the welding/rolling direction, the plate. All the pieces were cut at a width of around 11 mm with a band saw equipped with a lubrorefrigeration system. It's really important to cut without affect the sample with the heat due to the operation that's why the system used a large amount of liquid. The initial and the ending part of the plate were rejected because full of defects from the HYB process. The process at the beginning doesn't have the right temperature and the extruder needs a short travel to work properly. Some specimens after the initial cut are on figure 3.4. The plate partition is visible in the figure 3.5 and explained in the table 3.5.



Figure 3.5. Samples after cut

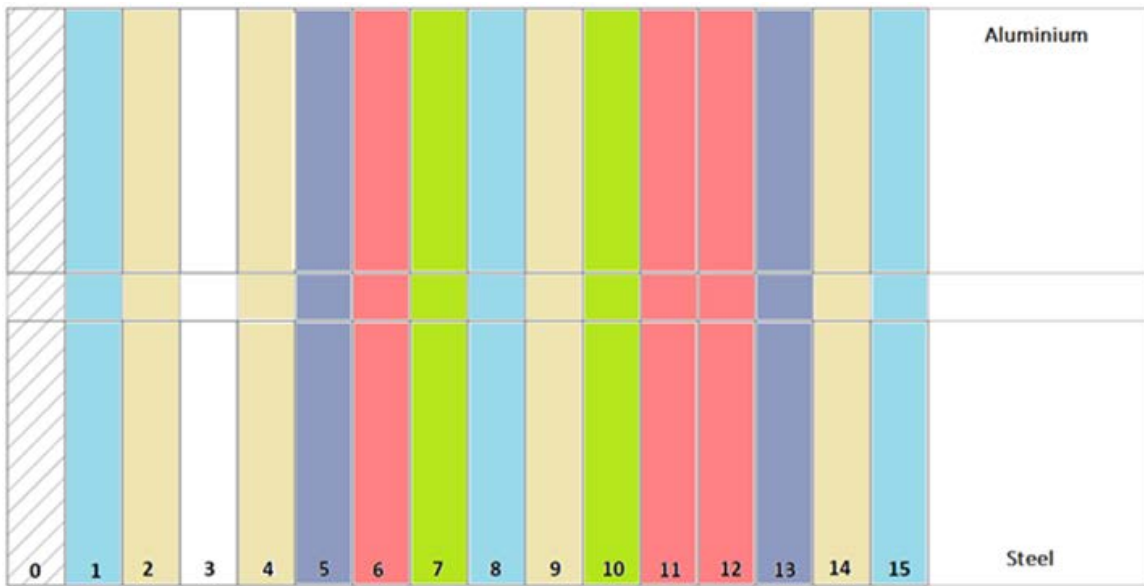


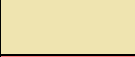






Figure 3.6. Plate partition scheme

Table 3.5. Plate partition

PLATE PARTITION		
Sample number	Use	Color
0	Scrap	
1, 8, 15	Tensile test	
2, 4, 9, 14	Tensile test NO reinforcement	
6, 11, 12	Microstructure	
7, 10	Vickers hardness test	
5,13	SEM microscope	
3	Further tests	

3.3.2 Sample preparation

For the microstructural investigation and the hardness testing the samples showed were shortened in their length to fit inside the vessel for the resin. Mount the specimens on the resin allow to operate the following steps in a better way.

Firstly, the samples were cut into sections of approximately 36mm with a circular saw for metals. This saw had a thin abrasive disc and a lubrorefrigeration system. It's important to cut a sample long enough to see the HAZ degradation. Therefore from the centre of the welding were cut more steel part instead of aluminium part, remembered the properties of the two materials. Figure 3.6 show a sample after the cut.



Figure 3.7. Samples before cold mounting

After cutting the samples were cold mounted in a ClaroCit acryl resin. The samples for the base material metallographic examination were obtained from the left pieces after the cut and mounted with the resin alone. The main specimens were fixed between two steel pieces of the same length. This reduce the edges rounding effect and give better results. In particular the steel is harder than the aluminium and without this adjustment the grinding process could give problems. The Figure 3.7 show the mounting operation.

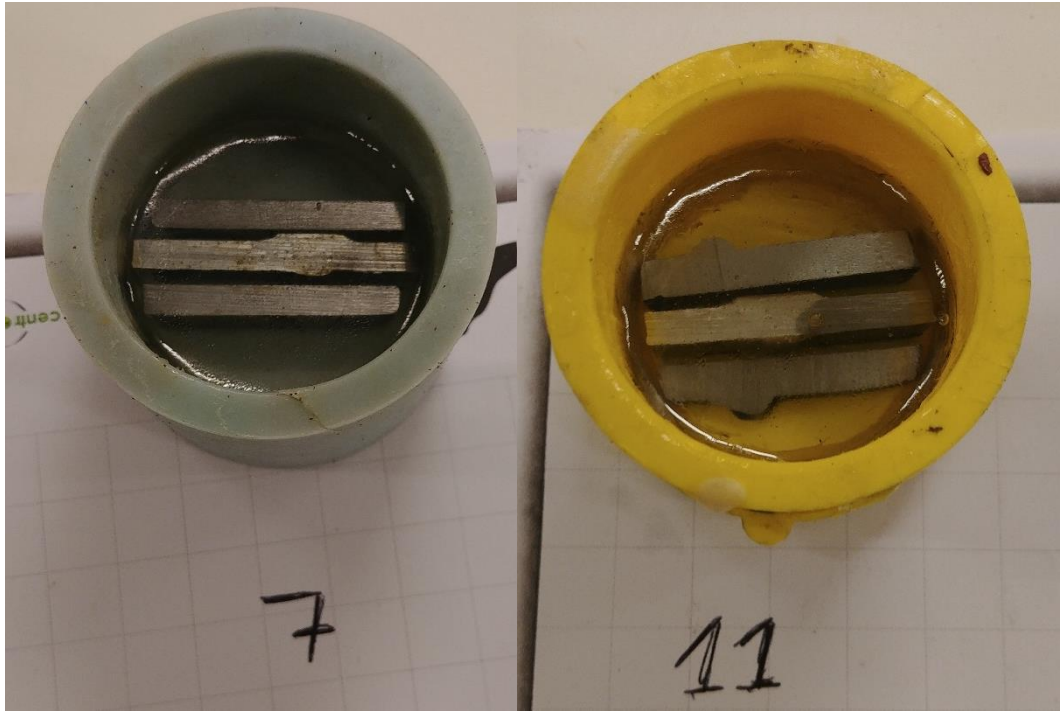


Figure 3.8. Mounting samples with ClaroCit resin

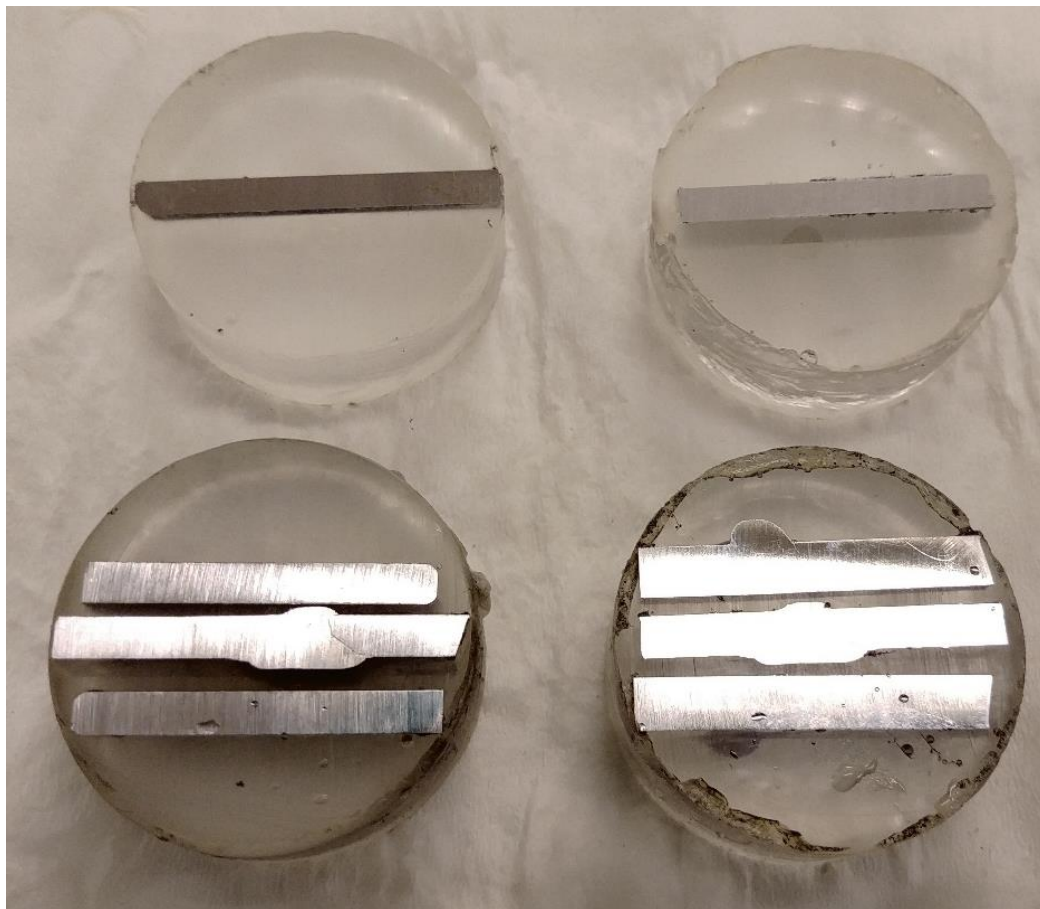


Figure 3.9. Mounted samples

The embedded samples were ground by using SiC grinding paper of increasing fineness (P120, P220, P500, P1000, P2000 and P4000). The machine used was a Jean Wirtz Phoenix 2000. Between each grinding step, the samples were cleaned with water and with ethanol. Attention was made on don't have scratches on the surface for every step.

After the grinding the samples were cleaned using an ultrasonic ethanol bath, then the polishing of the samples were carried out by using the Struers Knuth-Rotor 2 machine. For the process, two polishing disks were used because it was made in two steps: 3 μm and 1 μm . The abrasive was a diamond paste suspensions and a DP-Lubricant Blue was used as lubricant. Between the steps the

samples were cleaned by using an ultrasonic ethanol bath for few minutes. It's really important to not contaminate the fine disk with larger particles.

The ground and polished samples used for the microstructural examination were observed at the optical microscope to see the results and improve a better polishing if necessary. Finally, samples for the HV tests were ready, and the remain samples were ready for the etching process.

The two different materials need different solution to be etched. To analysing the aluminium microstructure an alkaline sodium hydroxide solution (*1g NaOH + 100ml H₂O*) were used. For the steel part an acid 5% Nital solution (*5 ml Nitric Acid+ 100 ml Ethanol*) were used. The holding time was around 150 s for the sodium hydroxide solution followed by 70 s for the Nital solution. After the double etching both metal showed the microstructure. The solution for one material didn't affect the other one. Finally, the samples were ready for microscope examination.

3.3.3 Optical microscopy

The analysis in the optical microscope was done using a Leica DMLB light microscope and an Alicona Infinite Focus Confocal Microscope. Samples were observed with different magnifications. Both etched and not etched samples were analysed.

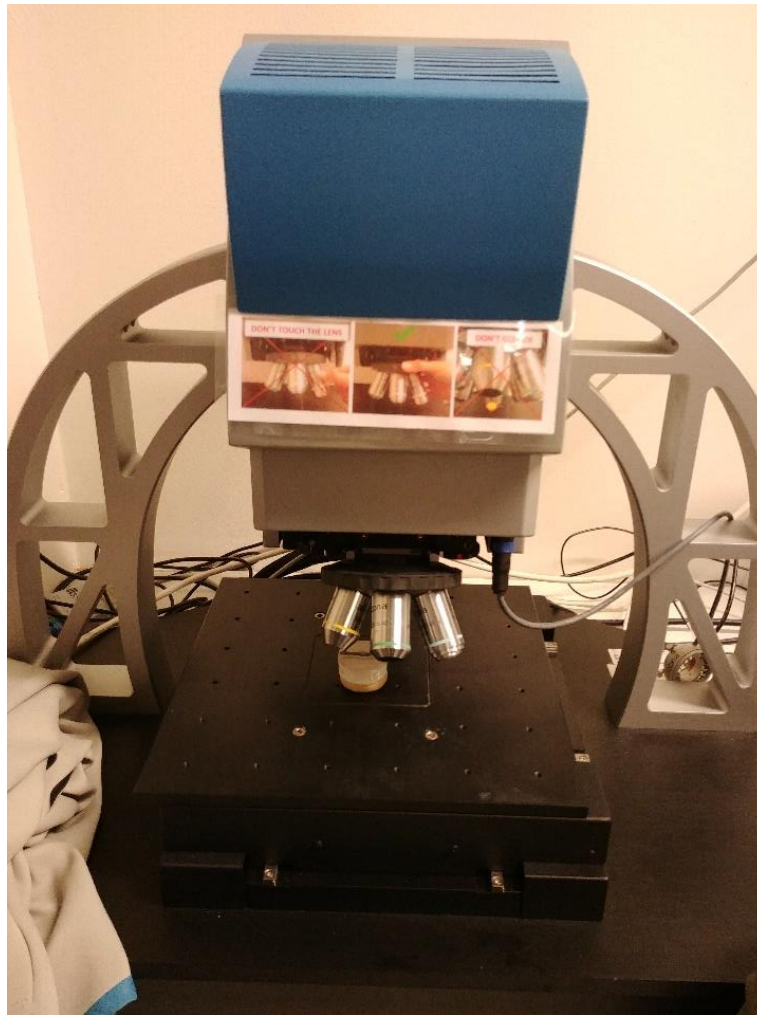


Figure 3.10. Alicona confocal microscope.

3.4 Hardness testing

The Vickers hardness (HV) was measured on two samples from different location, number 7 and 10. For each sample three different test series were conducted. In-between each test series, the sample was worked with the same process explained earlier: ground and polished. The hardness was measured both in the vertical and the horizontal sample direction on the middle of the joint. Moreover, the base metals hardness was done with individual random measurements on specimens of the original base material in before-welding condition.

A Mitutoyo micro Vickers hardness tester is used. To perform the test a weight of 1kg was applied during and as ASTM standard indicate, a minimum distance between two indentations of 2,5 times the value of one diagonal is maintained for a total of 0,5 mm. The machine is automatic for the indentation part. The operator has to move the sample fixed on a platform adjustable in two axes with two micrometres. For the high of the platform a knob controls the movement. After the indentation the operator has to align two black lines, visible from the machine's microscope, with vertices of the indentation in both vertical and horizontal directions. A view during the alignment operation is on fig. 3.13, were are visible the two materials and the different indentation. Then the machine gives the HV result. Pictures of the machine and of the samples tested are showed below.

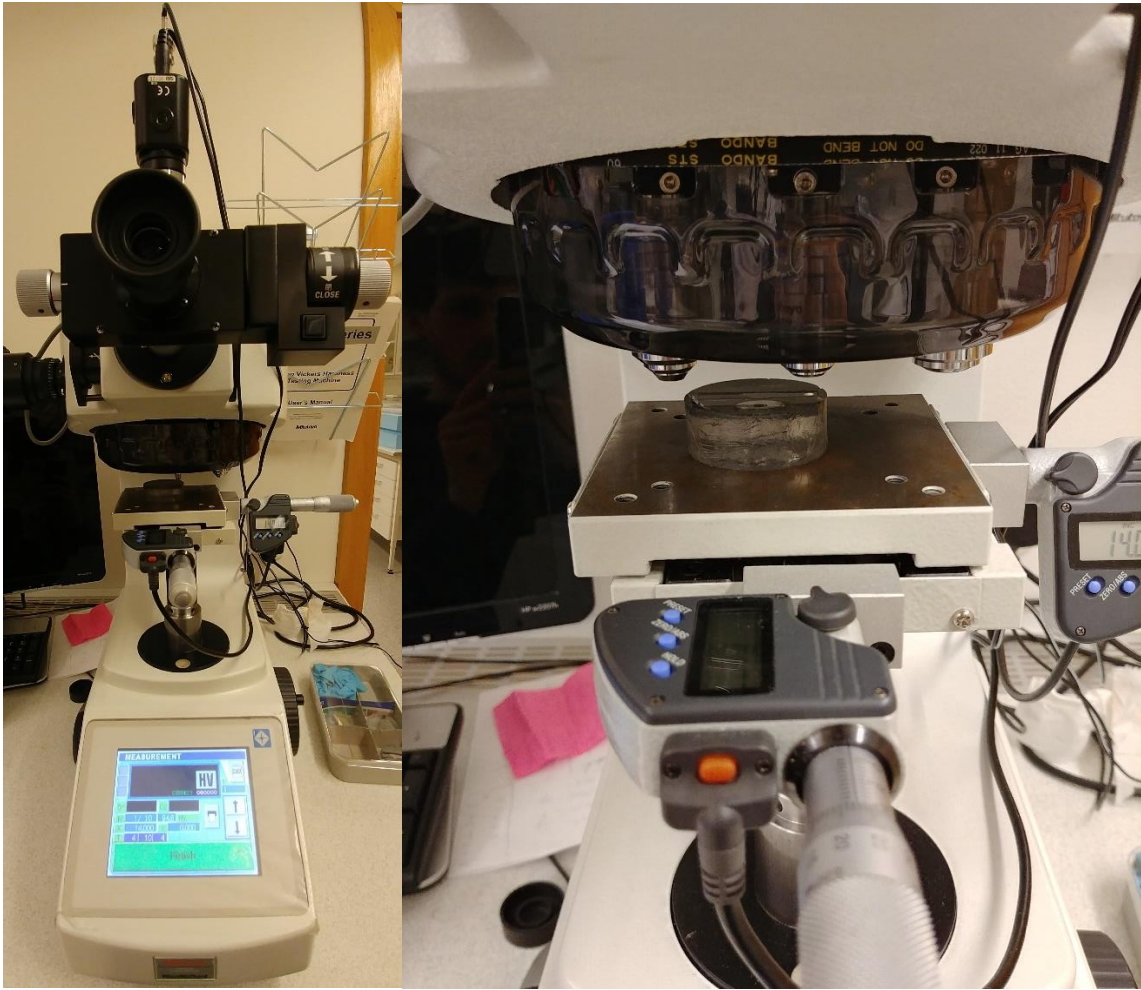


Figure 3.11. Mitutoyo micro Vickers hardness tester on the left

Figure 3.12. Detail of the fixed sample on the right

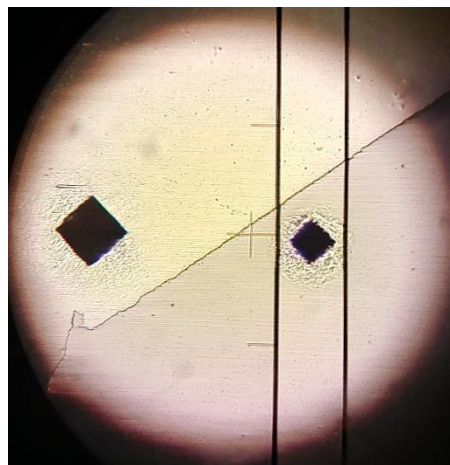


Figure 3.13. Detail of the view from the microscope of the Mitutoyo micro Vickers hardness tester. The steel is on the right with the smaller indentation and the aluminium on the left.

3.5 Tensile testing

The samples used for tensile testing were taken from different zones of the plate, in the initial part, in the middle part and in the ending part. The dimensions of the tensile specimens are in accordance with the *ASTM E8/E8M* standard with a gauge length of 25 mm. A model of the sample is shown in figure 3.11 and details of the real samples on fig. 3.12.

Four samples were flush-machined and three were tested with the reinforcement. One of the flush-machined were used for a test because ruined during the machining operation.

From the initial width of 11 mm the specimens were machined to 10 mm with a milling machine. The operation was delicate because the pieces can't be mounted on the clamp for the welding reinforcement. Two flat steel pieces were shaped to fit correctly the samples. Therefore the samples and the technical draw were given to the technician that made the “dog bone shape” with a CNC machine.

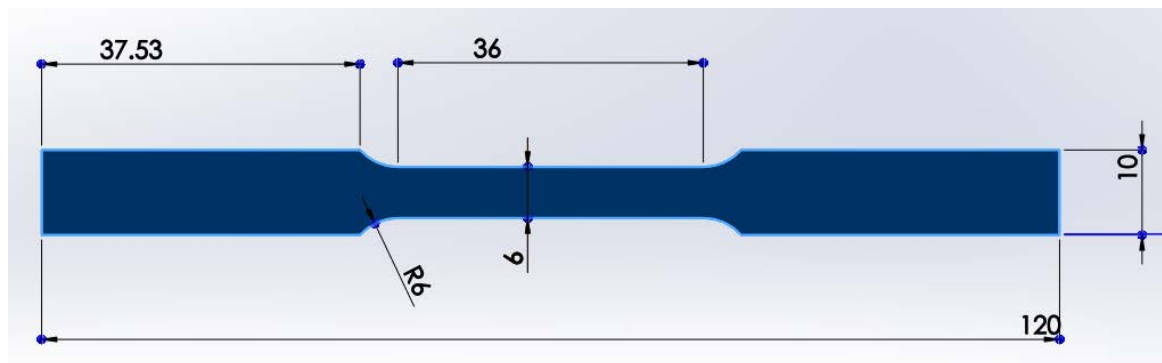


Figure 3.14. Model of the specimen with dimensions



Figure 3.15. Tensile specimen front view

Figure 3.16. Tensile specimen lateral view

Three samples were tested using an MTS hydraulic press with load cell of 50 kN at room temperature. The strain rate was fixed of $\dot{\epsilon} = 10^{-3} s^{-1}$ and the cross head speed was of the test was $v = 1.5 mm/min$ but without using an extensometer because it was not possible on the machine.

The other four samples were tested on an Instron 5985 machine with load cell of 250 kN with the same speed of previous tests. The test was carried out with an extensometer only on the aluminium part and with a digital image correlation (DIC) measurement system. The camera needs a pattern printed on the sample's surface (fig.) and allow to put virtual extensometers on the samples. The extensometer on the aluminium part had a gauge length of 10 mm. The instrument is only in the Al part because it's the one where the deformation is greater compared with the steel.



Figure 3.17. Tensile test with DIC.



Figure 3.18. Clamps with the specimen and the extensometer.

Figure 3.19. Samples with pattern on the right.

3.6 Scanning Electron Microscope analysis (SEM)

With SEM were observed the bonding area and the fracture surface of the broken tensile test specimens. The microscope is a Quanta FEG 450. The examinations were performed at an acceleration voltage of 20 kV and 30kV for both materials. The working distance was set to the limit to work safely, approximately 10 mm. The samples were cleaned well with ethanol before the analysis.

With specific clamps the samples were fixed inside the chamber. The fracture surfaces were observed with the samples in vertical position (fig. 3.14). The bonding area were observed from the resin mounted samples for searching IMC: they were fixed with a flat surface on the platform; they were free of resin in the bottom.



Figure 3.20. SEM at NTNU laboratories

Figure 3.21. A specimen mounted on the SEM

4 Results

4.1 Microstructure examination

4.1.1 Base material

Firstly, the BM microstructure is shown to understand what the metals look like without distortions from the process. The images that follow are taken after an NaOH etching for the aluminium part, that reveals fibres, and precipitates. For the steel, the Nital etching is used. In the aluminium, grains are barely evident due to high deformations of the material. The steel microstructure is really evident with his grains. On the Al part is visible the rolling direction.



Figure 4.1. Aluminium BM

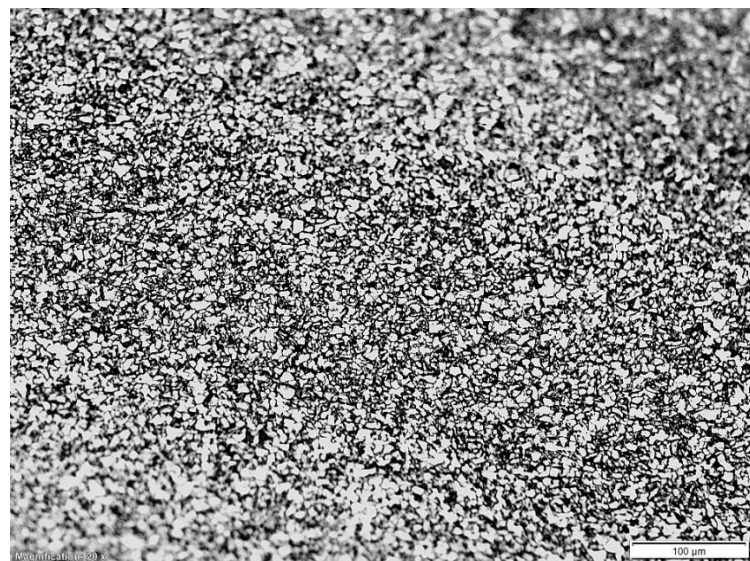


Figure 4.2. Steel BM

4.1.2 HYB joined material

An overview of the etched sample is on fig. 4.3. Both metal are etched and the aluminium show the differences between the base material and the filler material. The filler material show the flow pattern due to the extrusion process. On the bottom and on the top the material is in excess and form the reinforcement. That excess is made both of filler and of BM Al that is pushed in the process. The bond between the FM and the Al BM seems to be gradual, without showing discontinuities.

There is a high material strain on the centre zone due to the rotational spindle. The spindle provides a good mixture of the Al FM with the BM and this gives a good bonding.

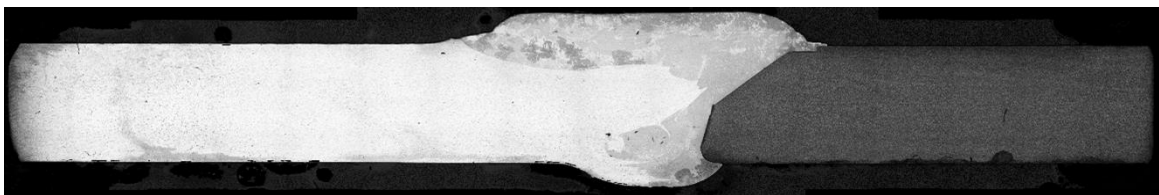


Figure 4.3. Overview of the etched sample

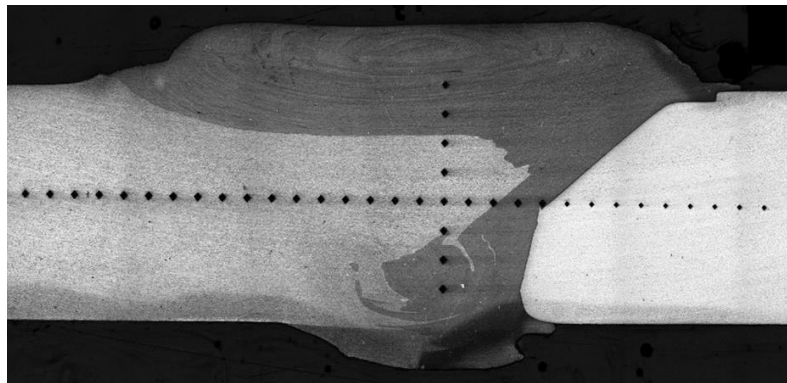


Figure 4.4. Detail of the welded zone. Only the Al part is etched.

Details of the flow pattern are on figure 4.4. On fig 4.5 there is a detail of a lack of bonding on the top part of the sample. The material flow outside the central zone and reach the top part of the steel. Here the pression is low and the plasticized aluminium tries to interact with the cold upper surface without success. So there the bonding is difficult to obtain.

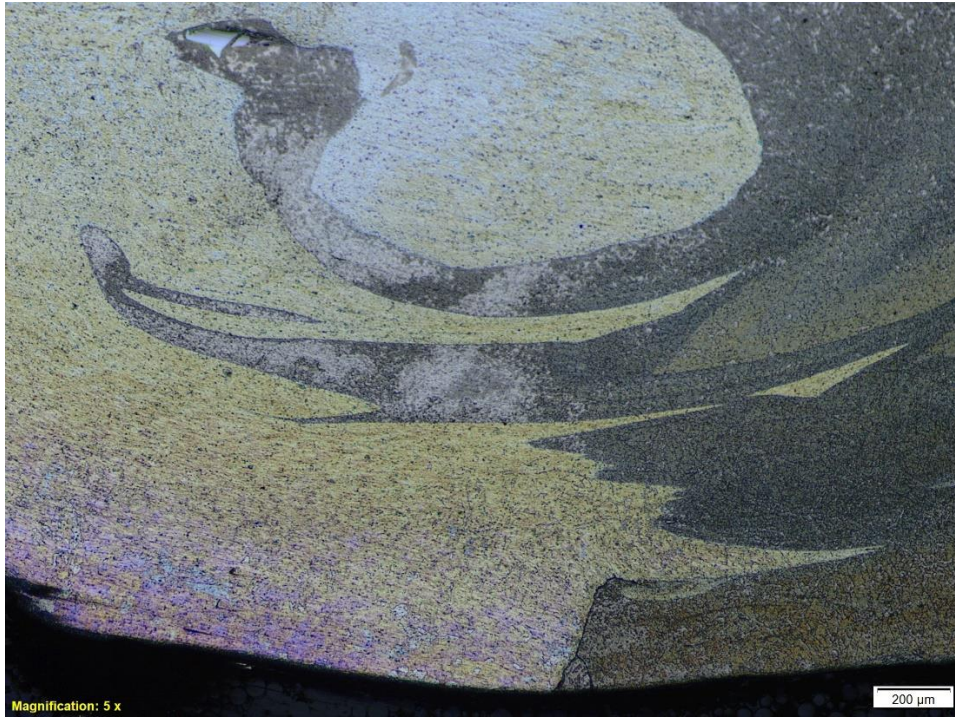


Figure 4.5. Detail of the filler material S6

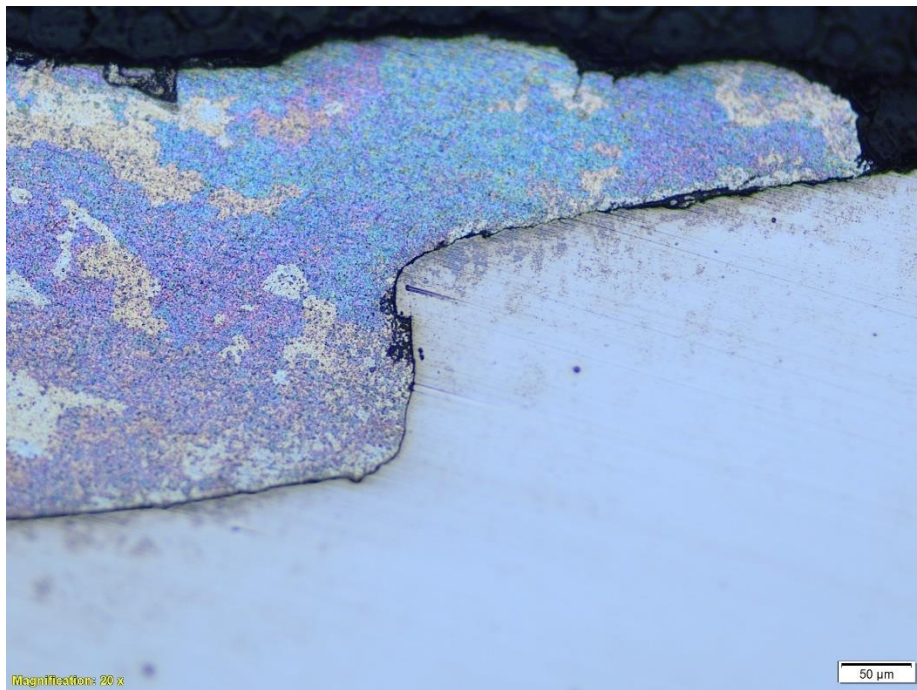


Figure 4.6. Detail of a lack of bonding S11

The details of the sample show the microstructure in both the metals. The grains are visible.

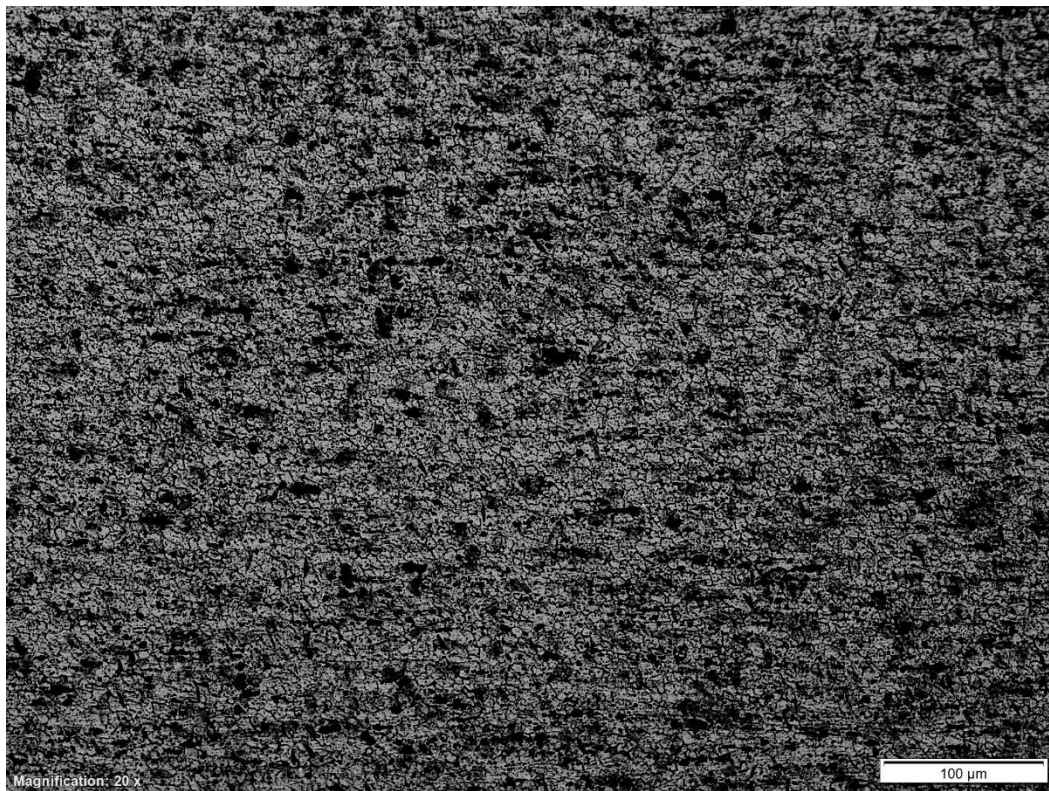


Figure 4.7. Al close the joint

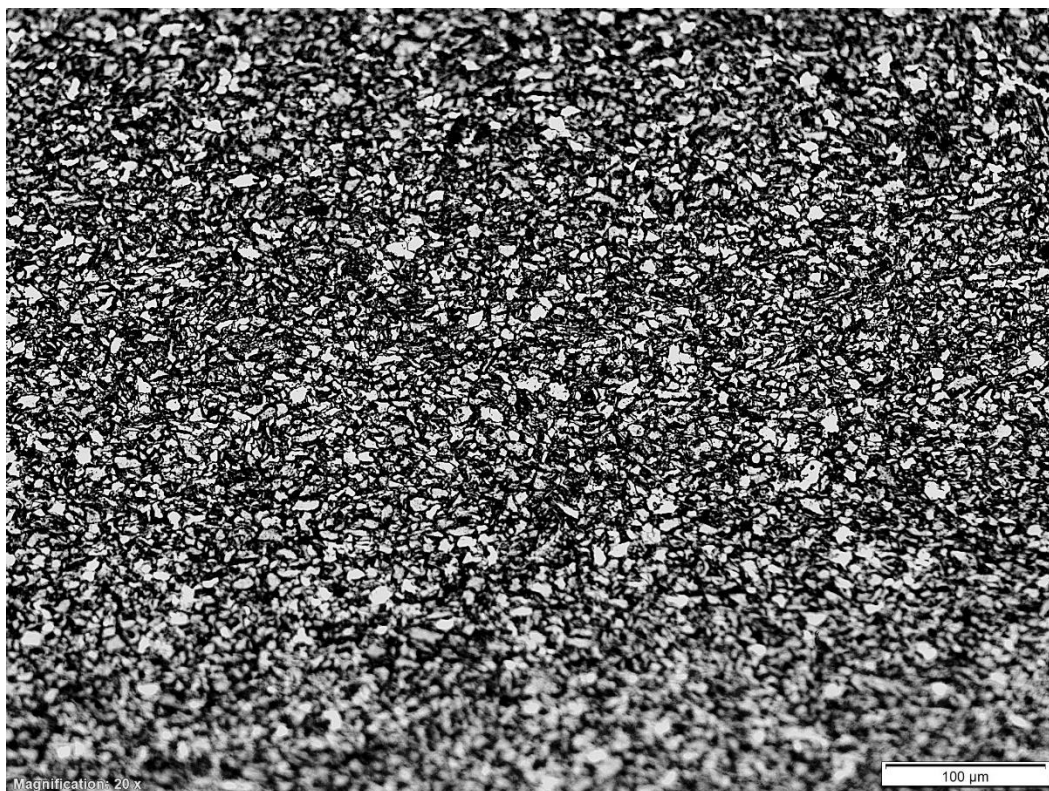


Figure 4.8. Steel close the joint

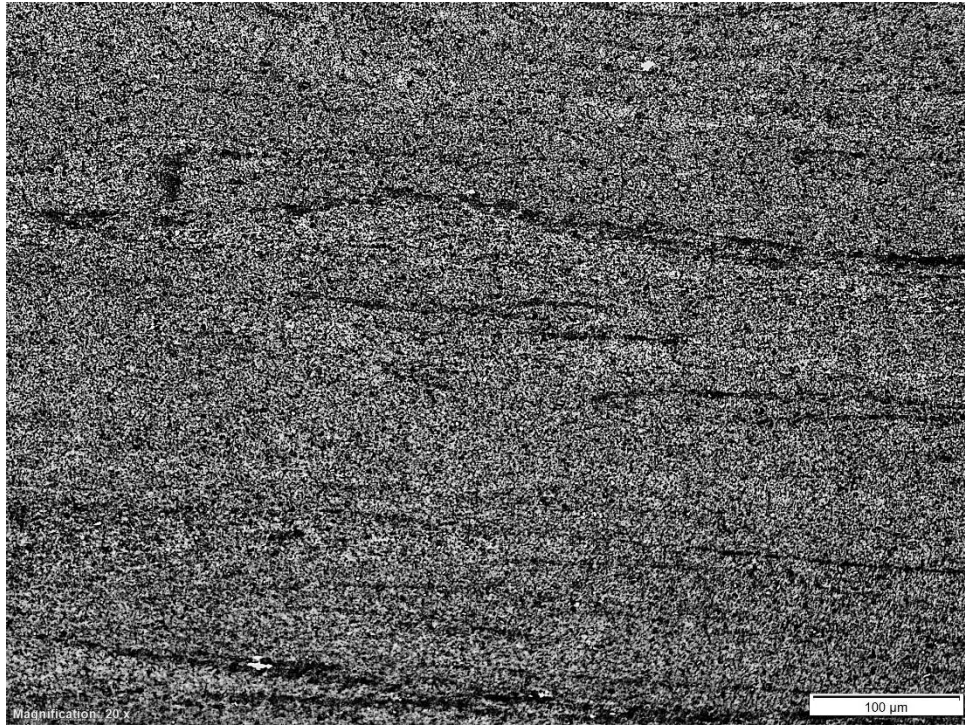


Figure 4.9. Al filler material FM

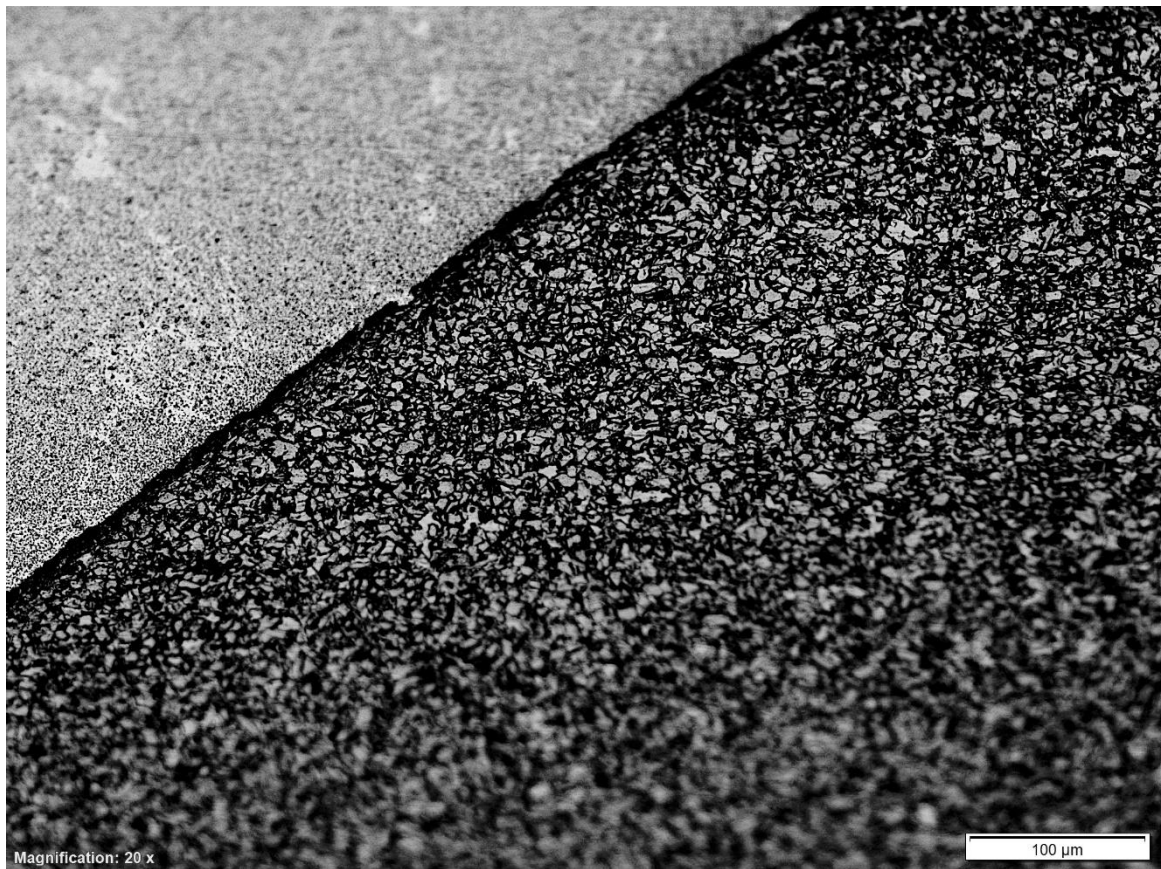


Figure 4.10. Detail of both metals and the bonding line

4.2 HAZ with hardness test

The hardness test is extremely important and took a lot of time to have a large amount of data. Samples 7 and 10 were used for this test, and three series of hardness test were done for each sample. Two paths were repeated: one in horizontal and one in vertical direction. The starting point was the middle of the welding area.

The mean values of the hardness results on the BM are 110,9 for the aluminum and 164,6 for the steel. Higher values were founded from the centre to the surface, due to the rolling process on the plates.

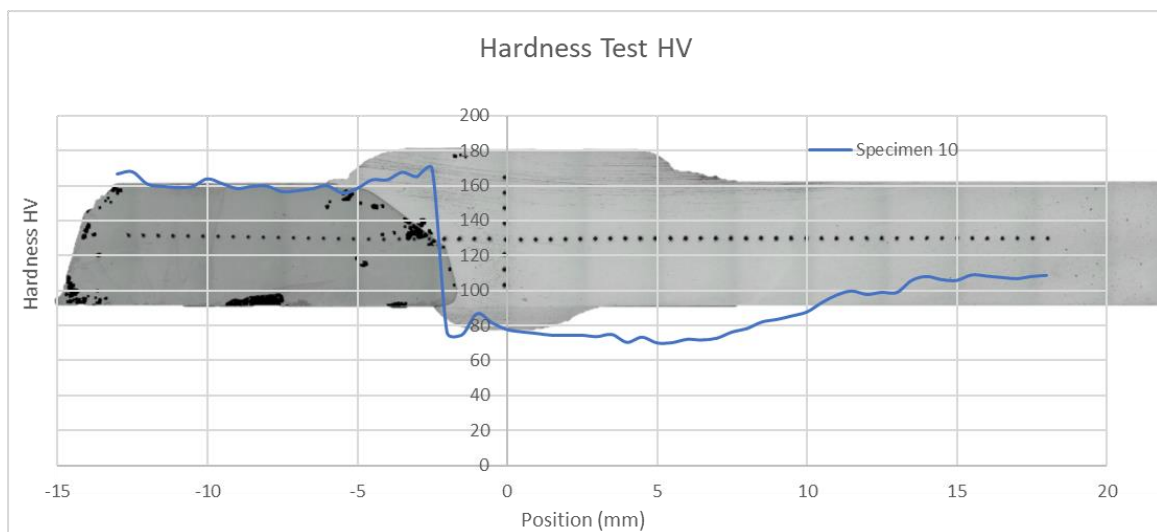


Figure 4.11. Horizontal hardness values in their position on the welding.

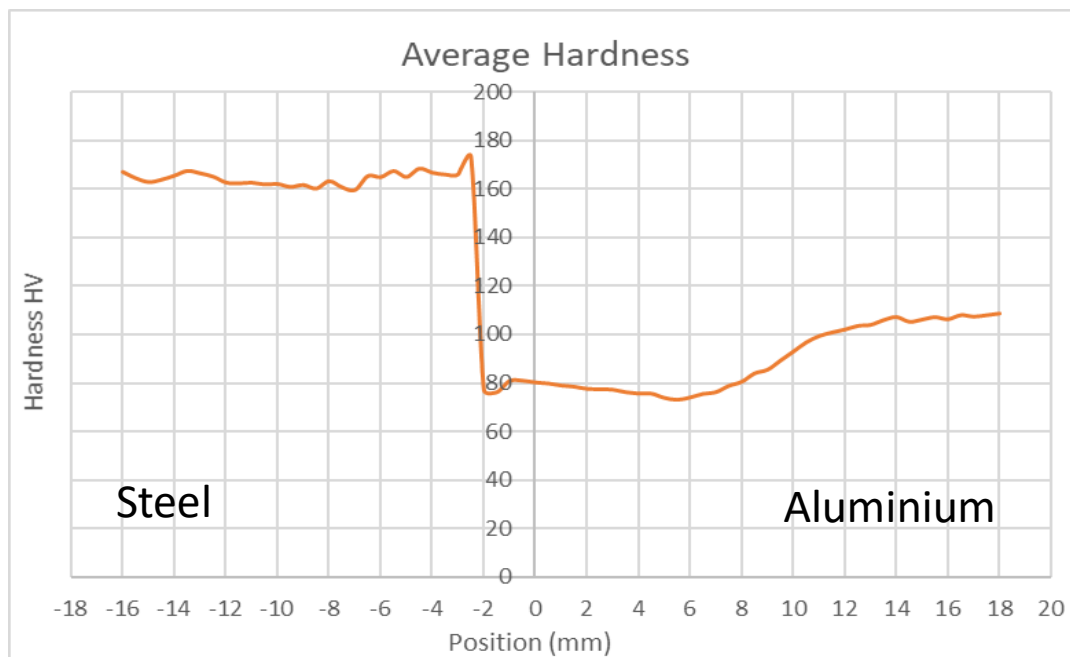


Figure 4.12. Average hardness HV of all the tests series, horizontal path

The horizontal hardness trend provides interesting information about the welding process. It's visible that a softening effect does almost not affect steel. The hardness difference between the two materials is clear. Aluminium on the other side suffer of a softening effect that disappears after 12 mm from the centre and this indicate the HAZ. Thus, as thought, aluminium turns out to be the weakest. The middle part until 5 mm there are the softer values, then proceeding to the unaffected Al the hardness increases again.

The vertical path is considered on figure 4.11. The hardness decreases from the top to the bottom in the vertical path. On the upper part, the increase of hardness reaches almost the same level of the BM at the top of the flash. The hardness path taken in two directions shows, on the aluminium side, the presence of a little TMAZ near the mixed area.

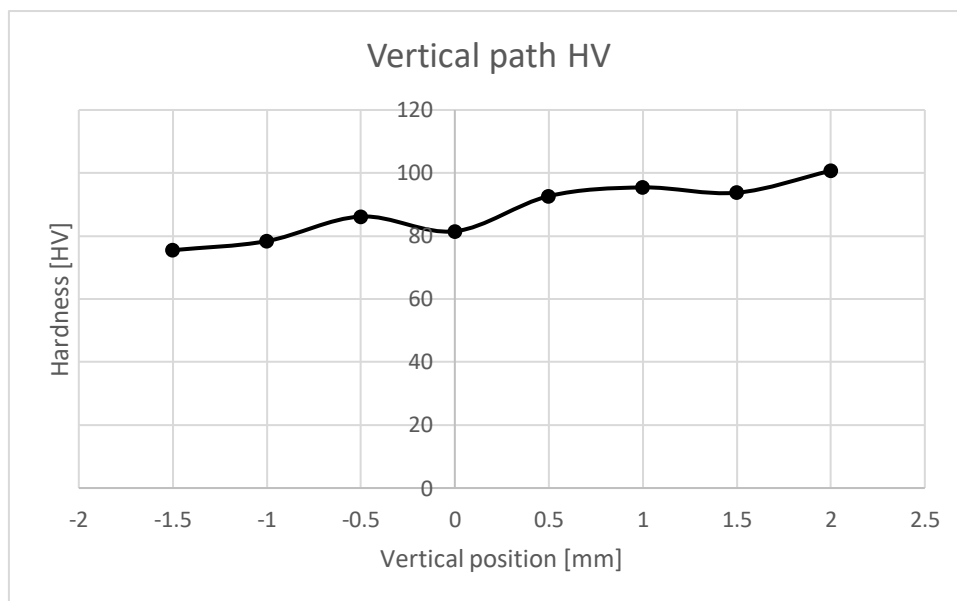


Figure 4.13. Average hardness HV of all the tests series, vertical path

4.3 Tensile test results

The tensile specimens were taken from different locations in the welded plate to see the differences on position.

The maximum load is shown on the table 4.1. The first three specimens have the reinforcement. S1 at the beginning of the plate suffer for the not perfect condition at the

early stages of the process. S15 is far from the end but has a decrement on the load. The specimens with letter F are flush-machined. S9R was ruined during the milling process and as expected the force to break it is lower. S14F is low too so it seems that at the end of the plate the bonding is weaker than in the middle.

Table 4.1 Maximum load of specimens

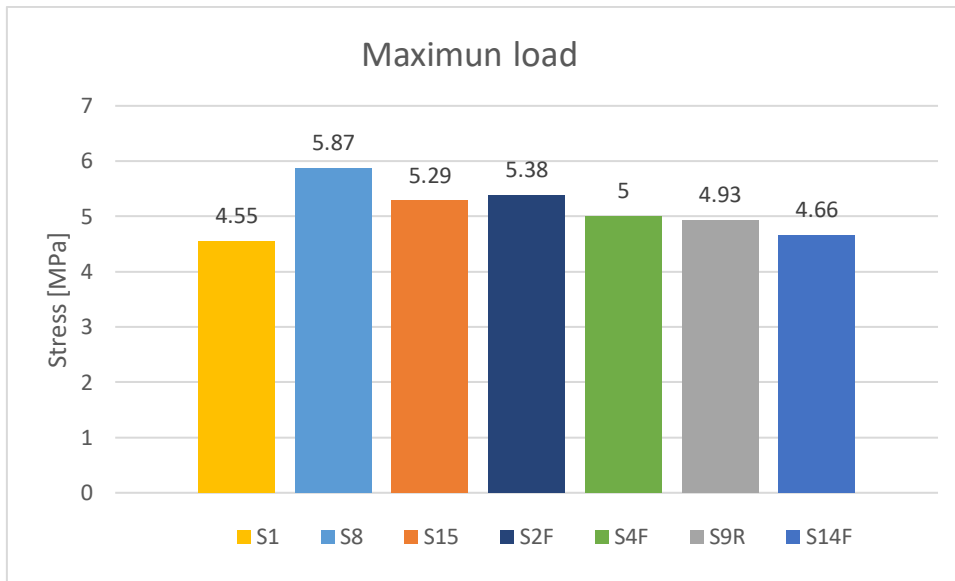


Table 4.2 Tensile tests results

Sample	Area [mm ²]	Max load kN	Max stress Mpa
S1	23.82	4.55	191.02
S2F	23.66	5.38	227.39
S4F	23.86	5.00	209.56
S8	23.85	5.87	246.12
S9R	22.5	4.93	219.32
S14F	23.72	4.66	196.46
S15	23.78	5.29	222.31

The results show that the joint resistance can reach up to 246 MPa of UTS, 74% of the Al BM strength.

4.4 Fractography of tensile specimens

The fractographic examination of the tensile specimens was carried out with the SEM. Micrographs of the fracture surface at low and high magnification are shown. With this instrument lighter material corresponds to higher density, and in this case the steel. With this analysis is possible to search the IMCs, dangerous for the bonding.

On figure 4.21 the steel part is marked with circle line to show where there is aluminium due to a perfect bonding area. Observing that area with a higher magnification is possible to see dimples because the fracture is of the ductile type.

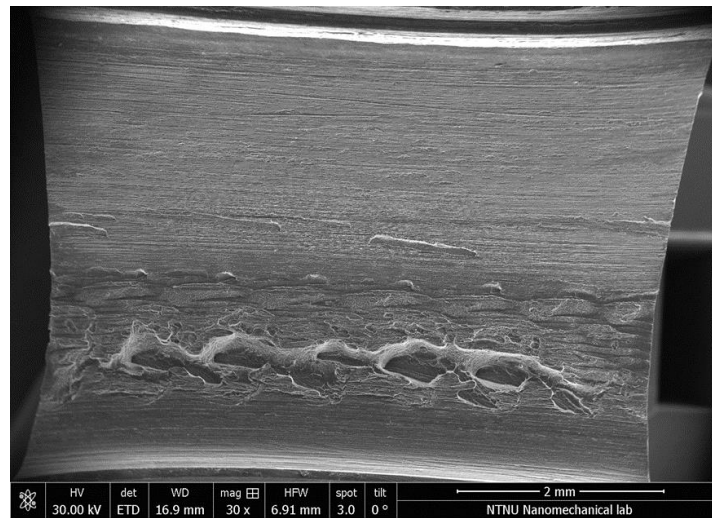


Figure 4.20. Fracture overview, S15, ALUMINIUM

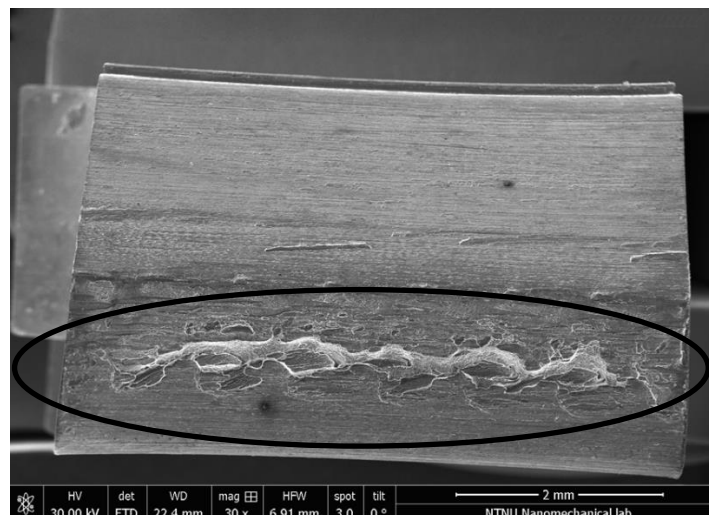


Figure 4.21. Fracture overview, S15, STEEL

From the fracture overview not all the steel area has aluminium on it. This is because the bonding is not perfect on all the surface. The joint has different level of bonding depending on the position.

With higher magnification on the Al attached on the steel some voids are clear. There we have ductile fracture

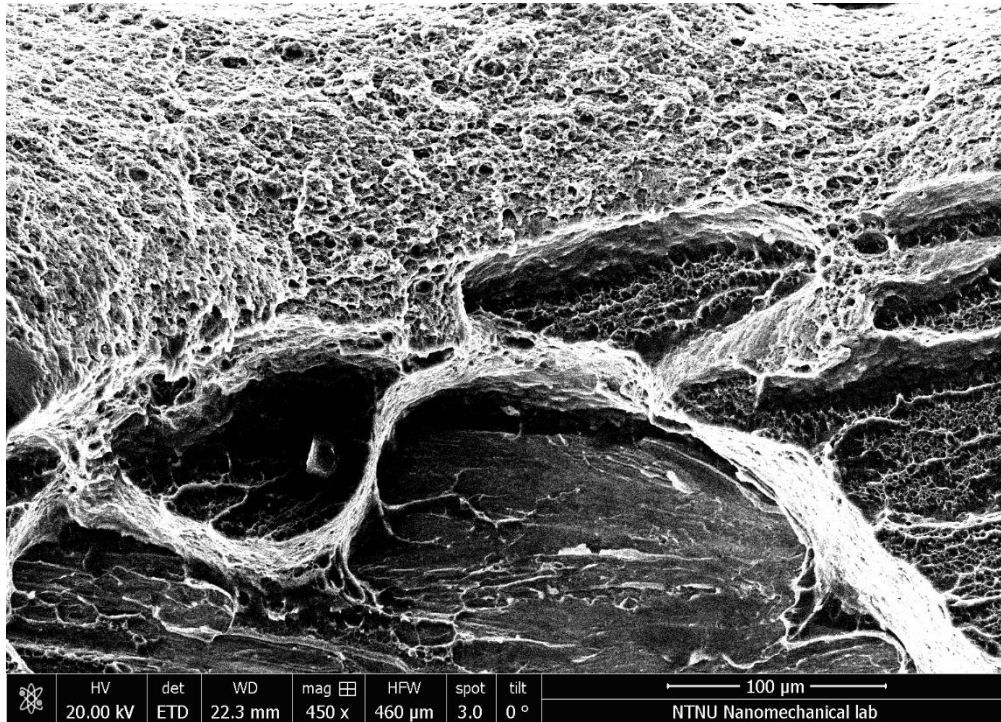


Figure 4.22. Al on steel part

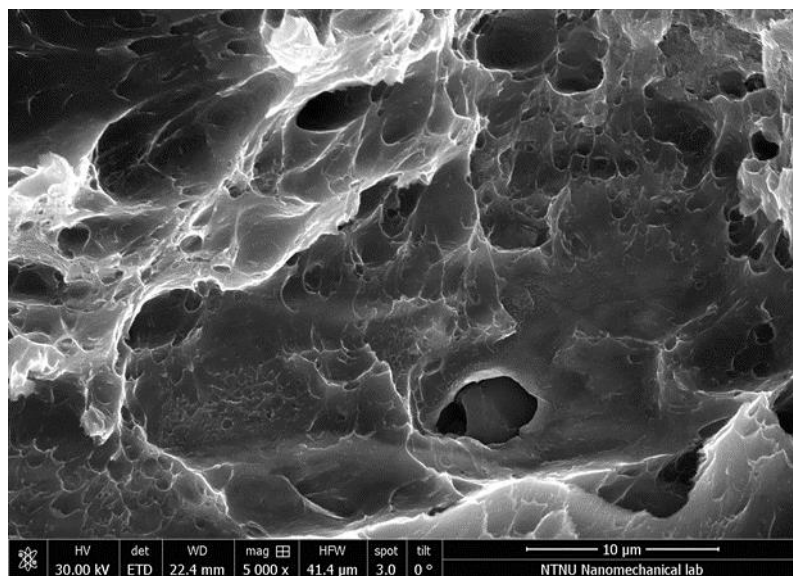


Figure 4.23. Al on steel part, detail

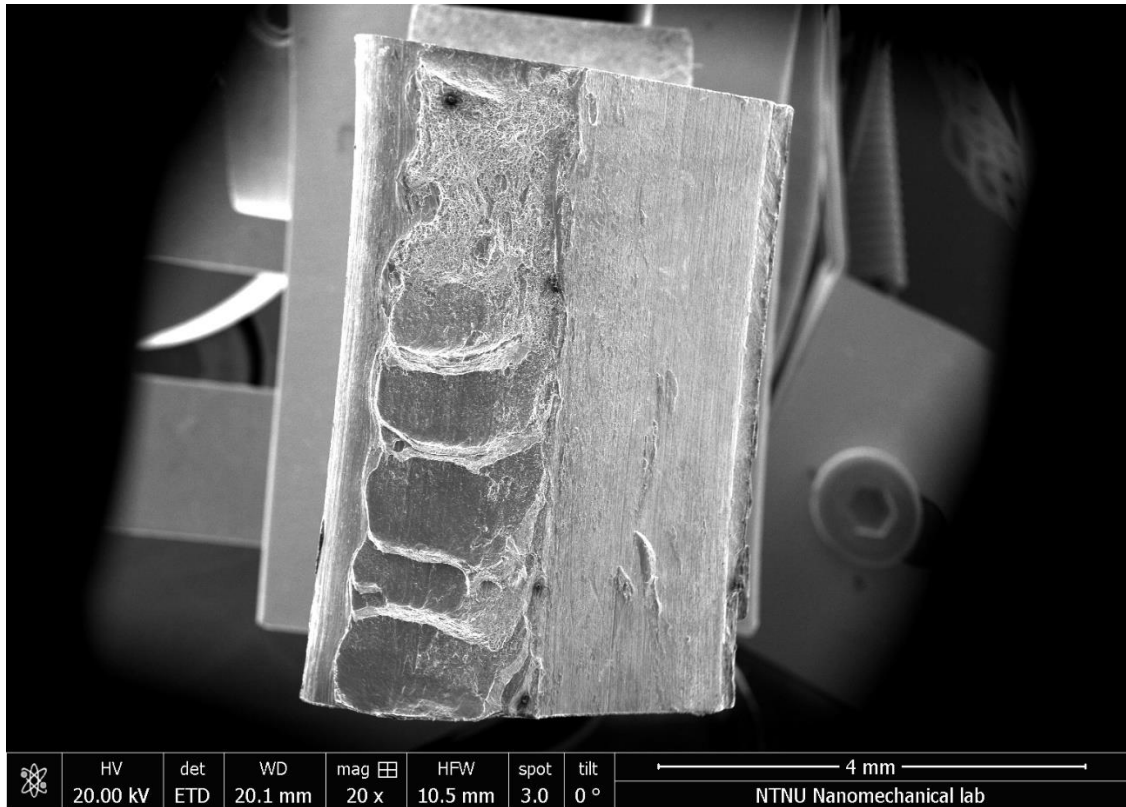


Figure 4.24. Fracture overview, S1, STEEL

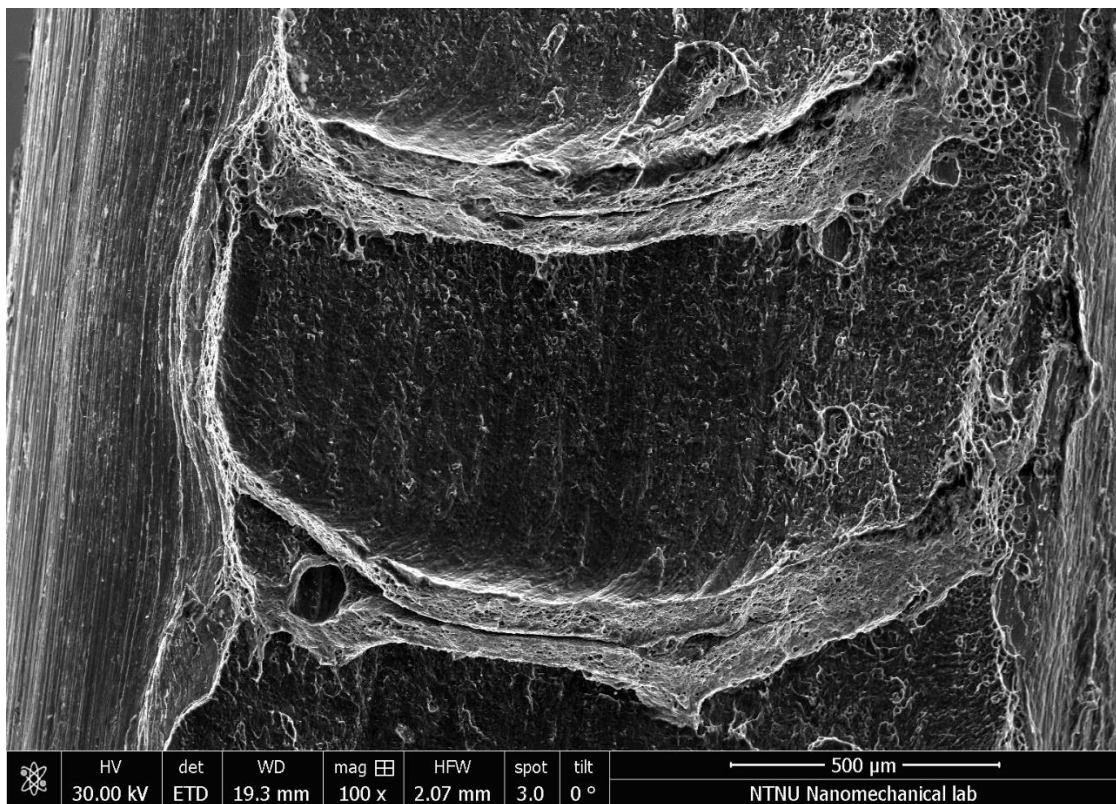


Figure 4.25. Fracture detail, S1, STEEL

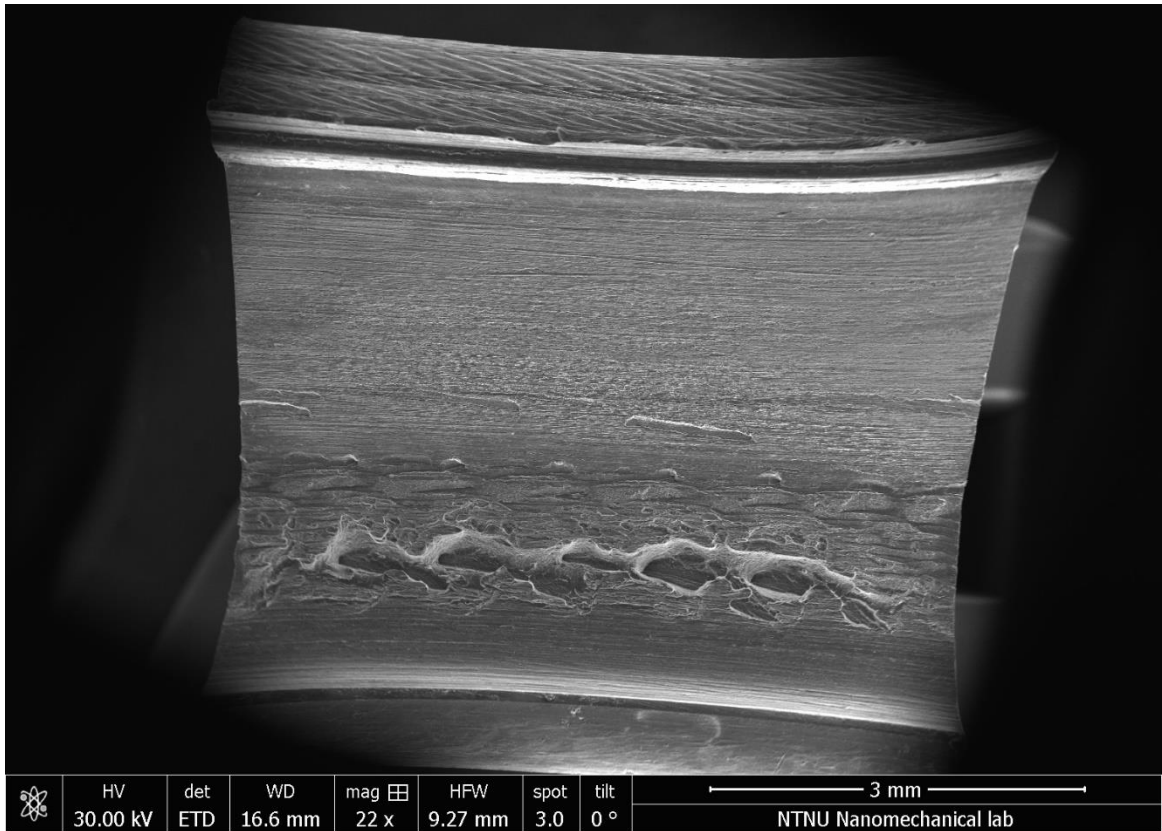


Figure 4.26. Fracture overview, S15, Al

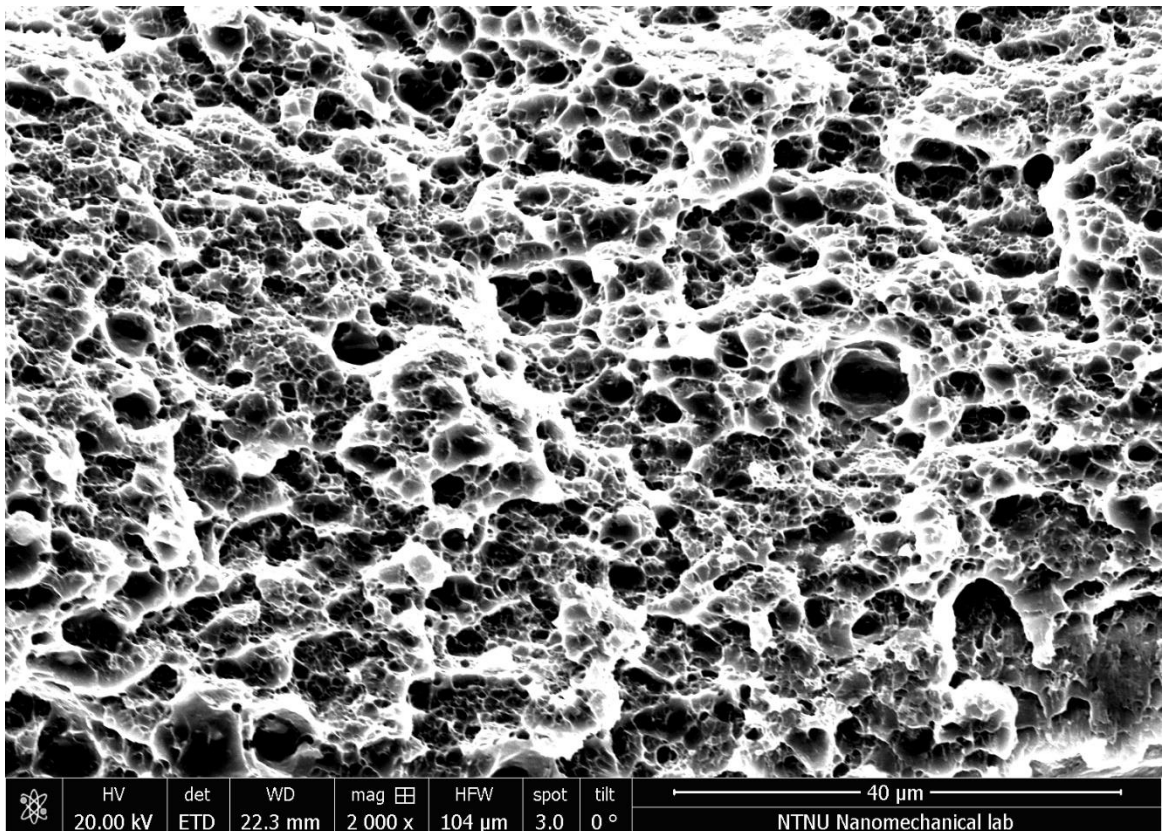


Figure 4.27. Fracture detail, S15, Al

The last step is the research of IMCs. Here some pictures took on different places along the bonding surface. On the sample is marked with a circle the position from where the detail come from, then a series of images with increasing magnification are presented. The sample analysed is S5. The positions analysed were from the bottom to the top of the plate, for searching differences in the behaviour linked on the position.

No IMCs were detected during the examination.

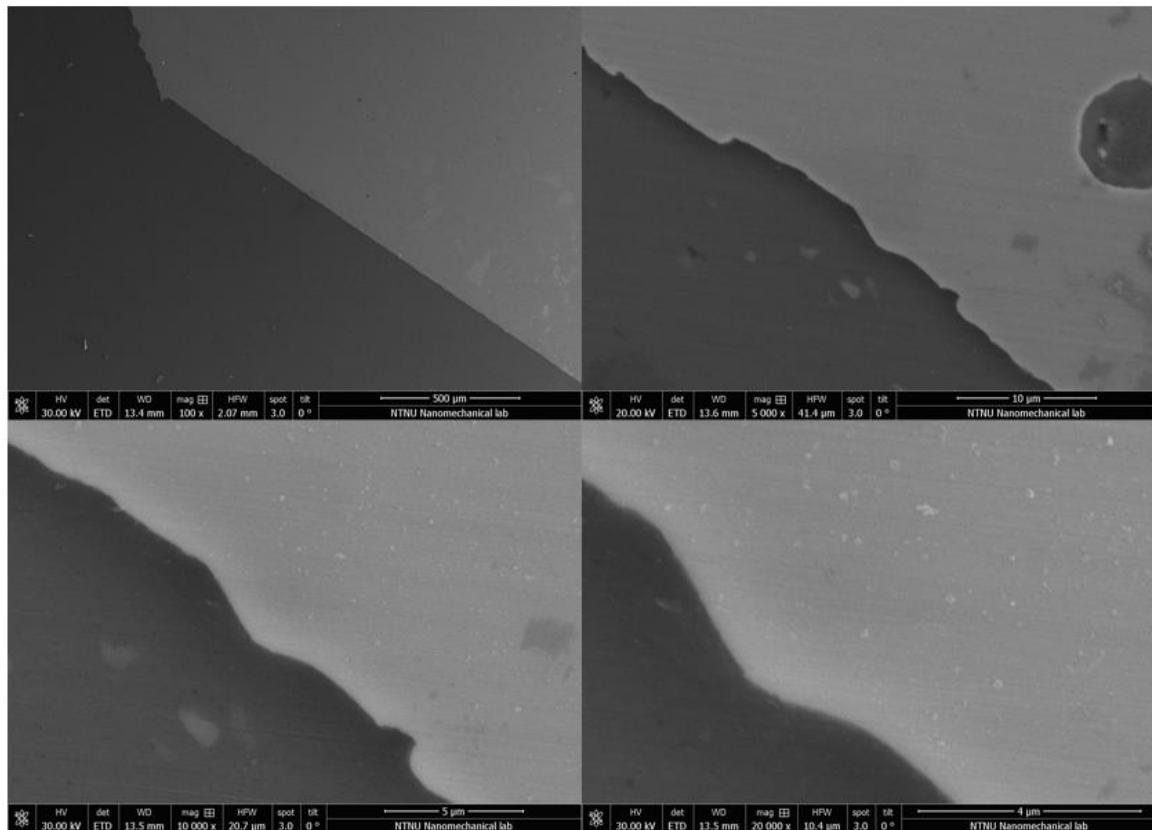


Figure 4.28. IMC research

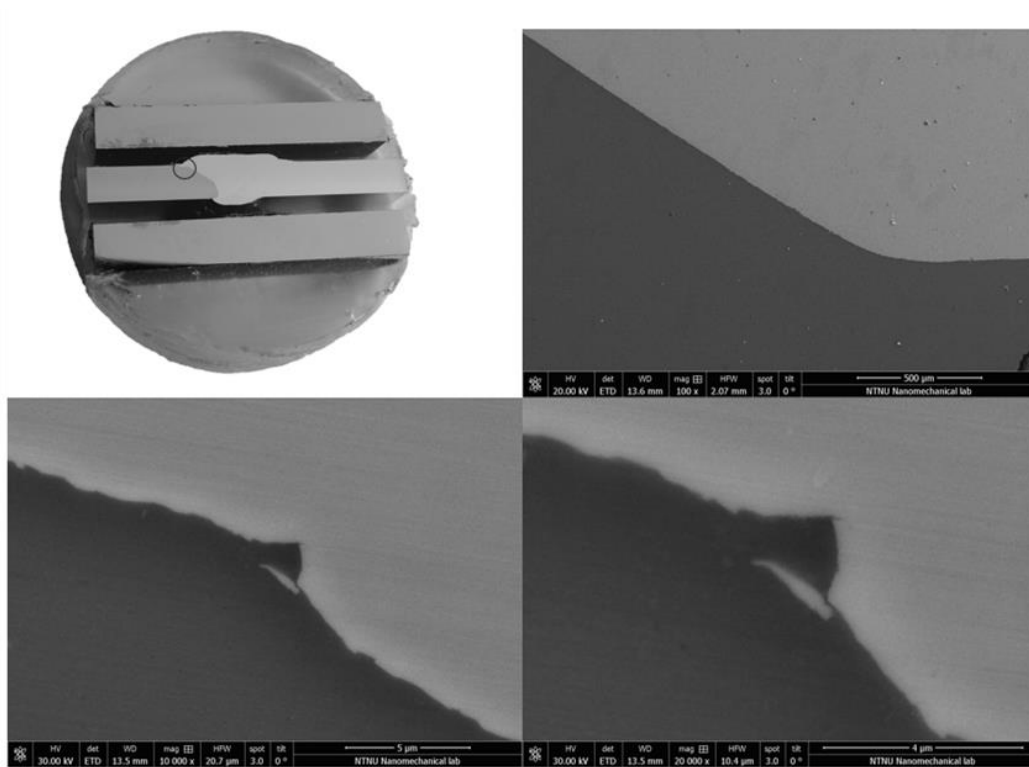


Figure 4.29. IMC research

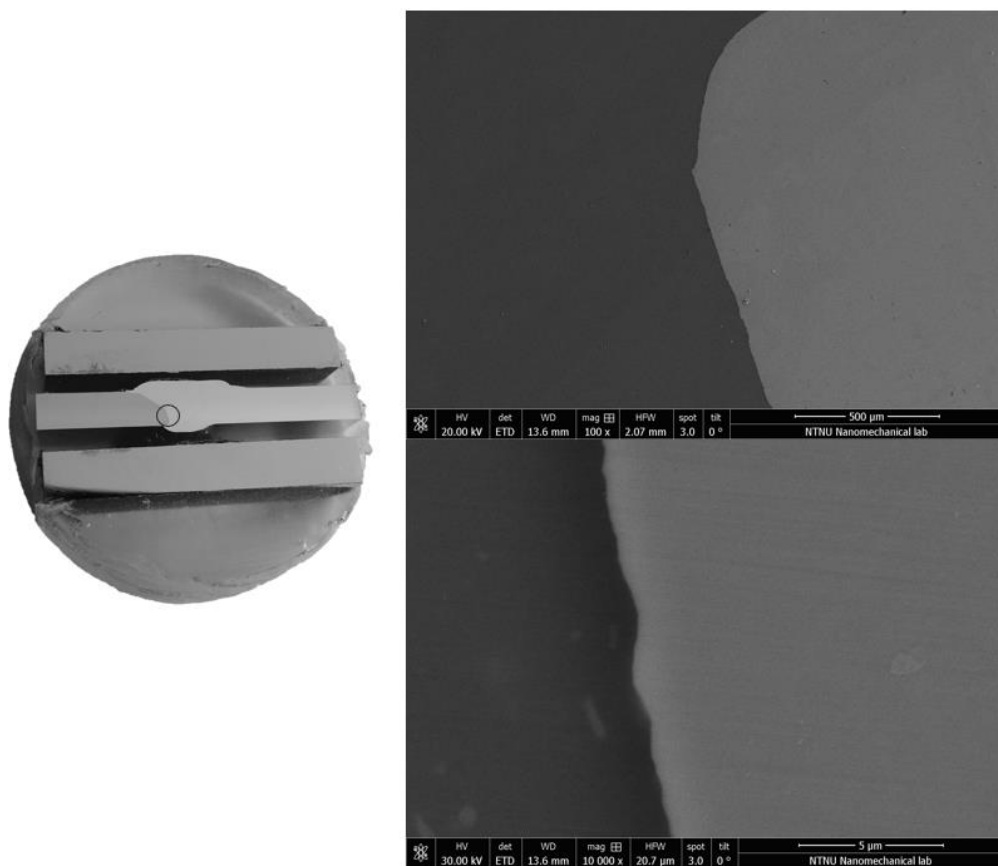


Figure 4.30. IMC research

5 Discussion

This chapter compares the principal results that have been obtained with those of other similar works.

It's interesting to compare the tensile test results with values from other technologies to clarify the potentialities of this welding method.

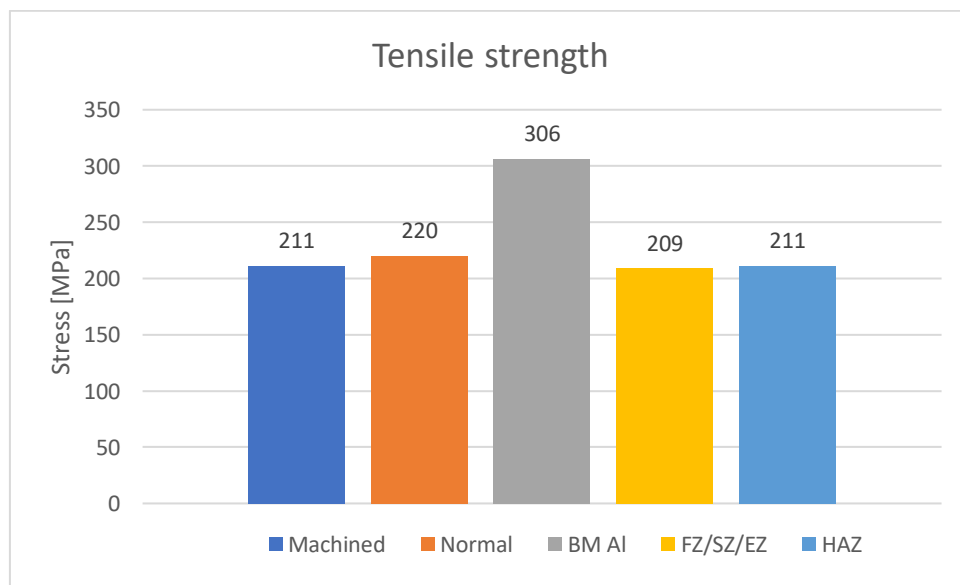
The best UTS from the tensile test was 74% of Al BM UTS, so this is a great value by considering that the same properties of Al BM are impossible to reach after a welding process.

It has been compared UTS with Al and not with steel because the fracture takes place in the weakest material. The results obtained from the fracture analysis shows the part with perfect bonding broke as Al BM, if we consider just that area the UTS is almost the same of the base material.

In the table 5.1 the comparison between UTS from HYB process on only AA6082-T6 plate is shown. The data comes from Lise Sandnes Master Thesis. Lise's specimens were machined, so they should be compared with the machined samples from this work.

The results are interesting because the tensile strength is the same, so the HYB method on dissimilar joint is strong as the HYB on two plates of the same material.

Table 5.1 Comparison HYB dissimilar and same materials. Data from Lise Sandnes Master Thesis.



- Machined: samples without reinforcement

- Normal: normal samples
- BM Al: base material aluminium samples
- FZ/SZ/EZ: fused zone samples, HYB method Aluminium-Aluminium (from Lise Sadnes thesis)
- HAZ: heat affected zone zone samples, HYB method Aluminium-Aluminium (from Lise Sadnes thesis)

The fractography showed the perfect bonding appear in a lower part of the weld which indicated that the welding condition are better than in the rest of the area.

Another result previously expected is about the IMCs. With the SEM no IMCs were observed but this doesn't mean that are not on the bonding area. With the HYB process IMCs are so thin that a specific work is needed to find them. By using the SEM, the highest magnification for having pictures with good focus, had results with a scale of few micrometres. This means that the analysis had that limit and only further investigation with different techniques could show IMC.

In other studies, it's showed that the IMC thickness for the same welding technique with the same materials is around few dozens of nanometres. Tina Bergh, from NTNU / SFI Manufacturing, shared with me some results of his work about IMC on HYB dissimilar bonding. The picture below shows how IMCs appear with an indication of the length.

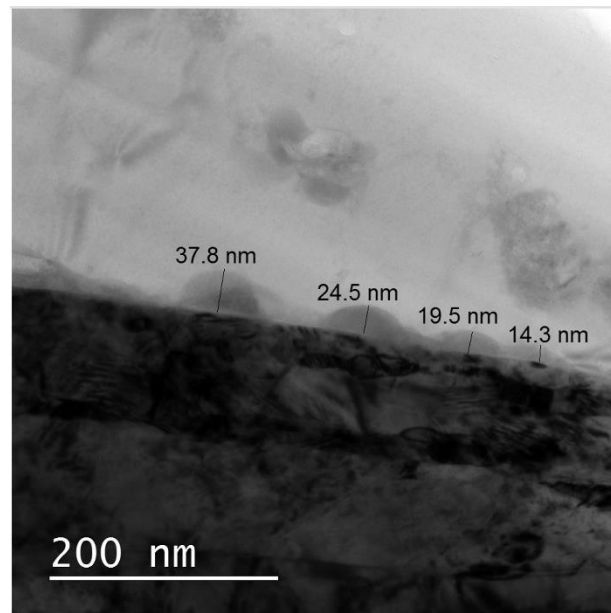


Figure 5.1. IMC HYB, from Tina Bergh (NTNU / SFI Manufacturing)

6 Conclusion

The characterization of HYB process is achieved. Thorough the analysis done and data collected it's possible to say that HYB cold-welding techniques in dissimilar joining gives good results comparable with results from joining of two plates of the same material.

The process is highly promising as opposed to the more spread cold welding techniques but need more studied on it.

The HYB PinPoint extruder is well suited for single pass butt welding of AA6082-T6 and S355. The resulting weld is free from pores and internal cavities and displays a very nice surface finish on both sides along all the welding path.

The hardness testing of the HYB weldment shows the presence of a HAZ in the aluminum side which is touch from the extruder Pin. On the other hand, steel is not touched and doesn't show a significant HAZ.

A good metallic bonding is achieved between the filler material and the steel base metal, as it has been demonstrated by tensile testing. The bonding is not perfect along all the butt joint but the strength is very high. In addition, the SEM investigation of the fracture surfaces revealed evidence of dimple formation in a large part of the bonding area which is compatible with a ductile fracture mode.

The fractography showed the perfect bonding is partially possible, so a further work on plates geometry and welding parameters could give better results.

References

- [1] G.M. Paolucci, Appunti di metallurgia , vol 2. 2001, Edizioni libreria Progetto
- [2] William D. Callister, Jr., Materials Science and Engineering; Department of Metallurgical Engineering The University of Utah
- [3] Yongchao Su, Xueming Hua, Characterization of intermetallic compound layer thickness at aluminum–steel interface during overlaying
- [4] Bhadeshia, H.K.D.H. and S.R. Honeycombe, Steels: Microstructure and properties. Third Edition ed. 2006: Elsevier Ltd.
- [5] Solberg, J.K., Teknologiske metaller og legeringer. 2013, Norwegian University of Science and Technology.
- [6] European Aluminium Association. The Aluminium Automotive Manual - Joining. 2015 [cited 2015 28.09.15].
- [7] R. Borrisutthekul, T. Yachi, Y. Miyashita, Y. Mutoh, Suppression of intermetallic reaction layer formation by controlling heat flow in dissimilar joining of steel and aluminum alloy, *Materials Science and Engineering A* 467 (2007) 108–113.
- [8] Potesser, M., et al., The Characterization of the Intermetallic Fe-Al Layer of Steel-Aluminum Weldings, in *EPD Congress 2006*. 2006, TMS - The Minerals, Metals & Materials Society
- [9] M. Potesser, T. Schoeberl, H. Antrekowitsch, J. Bruckner, The characterization of the intermetallic Fe-Al layer of steel-aluminum welding, *EPD Congress 2006*, edited by S.M. Howard, R.L. Stephens, C.J. Newman, J.-Y.J. Hwang, A.M. Gokhale, T.T. Chen, TMS (The Minerals, Metals & Materials Society), 2006.
- [10] J. Bruckner, Considering thermal processes for dissimilar metals-joining steel to aluminum in heat-intensive applications, *the Fabricator*, August 28; 2003,
<http://www.thefabricator.com/article/metalsmaterials/considering-thermal-processes-for-dissimilar-metals>.
- [11] F. Haidara, M.-C. Record, B. Duployer, D. Mangelinck, Phase formation in Al-Fe thin film systems, *Intermetallics* 23 (2012) 143–147.

[12] S. H. B. C. K. Martinsen, *Joining of dissimilar materials*; Sintef Raufoss Manufacturing

[13] J.L. Song, S.B. Lin, C.L. Yang, G.C. Ma, H. Liu, Spreading behavior and microstructure characteristics of dissimilar metals TIG welding-brazing of aluminum alloy to stainless steel, *Materials Science and Engineering A* 509 (2009) 31–40.

[14] H.T. Zhang, J.C. Feng, P. He, H. Hackl, Interfacial microstructure and mechanical properties of aluminium zinc- coated steel joints made by a modified metal inert gas welding-brazing process, *Materials Characterization* 58 (2007) 588–592.

[15] Pavan Kumar, N., S. Arungalai Vendan, and N. Siva Shanmugam, Investigations on the parametric effects of cold metal transfer process on the microstructural aspects in AA6061. *Journal of Alloys and Compounds*, 2016. 658: p. 255-264.

[16] L. Agudo, D. Eyidi, C.H. Schmaranzer, E. Arenholz, N. Jank, J. Bruckner, A.R. Pyzalla, Intermetallic FeAl₃-phases in a steel/Al-alloy fusion weld, *Journal of Materials Science* 42 (2007) 4205–4214.

[17] M. M. Atabaki, M. Nikodinovski, P. Chenier, J. Ma, M. Harooni, and R. Kovacevic, “Welding of Aluminum Alloys to Steels: An Overview,” *J. Manuf. Sci. Prod.*, vol. 14, no. 2, pp. 59–78, 2014.

[18] R. Qiu, C. Iwamoto, S. Satonaka, The influence of reaction layer on the strength of aluminum/steel joint welded by resistance spot welding, *Materials Characterization* 60 (2009) 156–159.

[19] R. Qiu, C. Iwamoto, S. Satonaka, Interfacial microstructure and strength of steel/aluminum alloy joints welded by resistance spot welding with cover plate, *Journal of Materials Processing Technology* 209 (2009) 4186–4193.

[20] M.J. Torkamany, S. Tahamtan, J. Sabbaghzadeh, Dissimilar welding of carbon steel to 5754 aluminum alloy by Nd: YAG pulsed laser, *Materials and Design* 31 (2010)

[21] T. Aizawa, M. Kashani, K. Okagawa, Application of magnetic pulse welding for aluminum alloys and SPCC steel sheet joints, *Welding Journal* 86 (2007) 119–124.

[22] Ryan M. Deacon; *Metallography, Microstructure, and Analysis*

- [23] J. Tsujino, K. Hidai, A. Hasegawa, R. Kanai, H. Matsuura, K. Matsushima, T. Ueoka, Ultrasonic butt welding of aluminum, aluminum alloy and stainless steel plate specimens, *Ultrasonics* 40 (2002) 371–374. Manufacturing using laser beam welding, *Welding Journal* (2013) 32–37.
- [24] F. M. Mazzolani, *Aluminium alloy structures*, 2nd Ed., E & FN Spon, London, 1995
- [25] P.D. Calderon, D.R. Walmsley, A. Munir, An investigation of diffusion welding of pure and alloyed aluminum to Type 316 stainless steel, *Welding Journal* 4 (1985) 104–112.
- [26] Naotsugu Yamamoto, Jinsun Liao, Shuhei Watanabe, Kazuhiro Nakata ,Effect of Intermetallic Compound Layer on Tensile Strength of Dissimilar Friction-Stir Weld of a High Strength Mg Alloy and Al Alloy
- [27] F. Findik, Recent developments in explosive welding, *Materials and Design* 32 (2011)
- [28] Y. Li, H. Hashimoto, E. Sakedai, Y. Zhang, Z. Zhang, Morphology and structure of various phases at the bonding interface of Al/steel formed by explosive welding, *Journal of Electron Microscopy* 49(1) (2000) 5–16.
- [29] E. A. Sandvik, “Cold Pressure Welding of Dissimilar Aluminum Alloys under Conditions Applicable to Hybrid Metal Extrusion & Bonding (HYB),” no. June, 2014.
- [30] *Standard Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials*. 2016, ASTM International
- [31] *Standard Test Methods for Tension Testing of Metallic Materials*. 2016, ASTM International.
- [32] Ulf Roar Aakenes Industrialising of the Hybrid Metal Extrusion & Bonding (HYB) method – from prototype towards commercial process. 2013.
- [33] P.M.G.P. Moreira , T. Santos, S.M.O. Tavares, V. Richter-Trummer, P. Vilaça, P.M.S.T. de Castro Mechanical and metallurgical characterization of friction stir welding joints of AA6061-T6 with AA6082-T6
- [34] G. E. Dieter, *Mechanical Metallurgy*, SI metric Ed., McGraw-Hill, London, 1988.