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Laser arc hybrid welding of thicker 6000-series aluminium alloy

Laser-MIG butt welding of 8 mm 6082-t6

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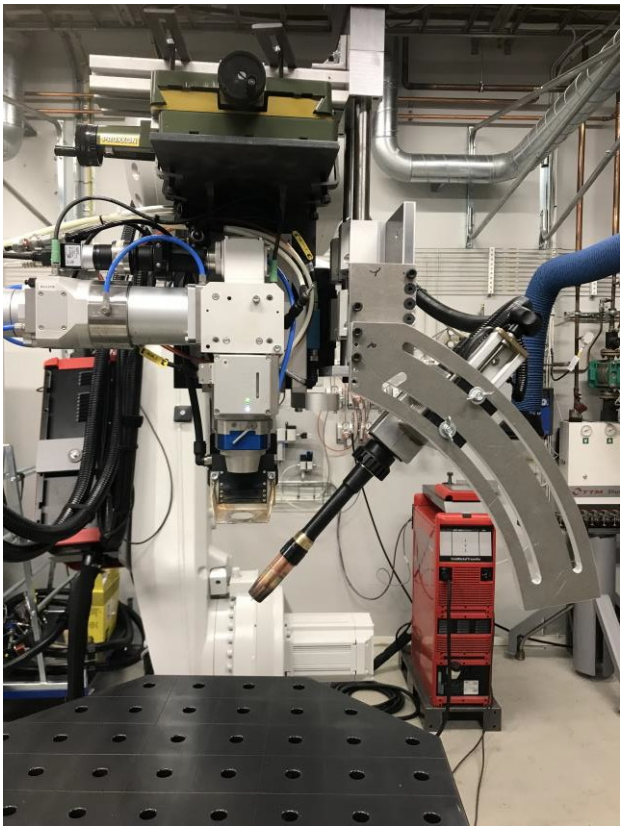

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Abstract

Laser arc hybrid welding presents many benefits but has many parameters that must be optimised for it to work. It becomes even more challenging when welding thicker aluminium with the process. Welding of thicker aluminium alloys involves a lot of different challenges, on itself. This thesis presents some theory about welding of aluminium alloys and theory about laser arc hybrid welding.

Welding trials on 8mm thick 6082 aluminium alloys is performed. A few welding parameters are tested and evaluated. A few welding speeds are chosen, and the laser power is chosen to the lowest possible to still achieve full penetration. The highest welding speed of around 4m/min is achieved at the maximum laser power at hand (10kW). A few autogenous laser welds are also welds as reference.

Welding trials with integrated backing strips are also tested.

The welding trials results in two process area which gives low porosity welds. At welding speed of around 0,5m/min and lower welds with low porosity can be achieved. Welding speed of around 4m/min and above also gives low porosity welds. In the process area between 0,5m/min and 4m/min the welds have a lot of porosity.

The reason for the porosity is probably keyhole instability.

Non full penetrating welds shows a lot of porosity in the lower part of the weld, this becomes obvious when welding with backing strip.

Most of the welds welded without backing material have sagging top and excessive penetration. Only welds welded at the highest welding speed gave welds within the quality levels of chosen standards.

Sammanfattning

Laser hybrid svetsning har många fördelar men många parametrar behöver optimeras för att processens ska fungera. Det innebär en ännu större utmaning när tjockare aluminiumlegering ska svetsas med svetsprocessen. Svetsning av aluminiumlegeringar innebär en del olika utmaningar i sig självt. Denna uppsats presenterar en del teori om svetsning av aluminiumlegeringar och teori om laser hybrid svetsning.

Svetsförsök på 8mm tjockt 6082 aluminiumlegering har utförts. En del svetsparametrar är testade och utvärderade. Några svetshastigheter väljs och den lägsta möjliga lasereffekten som fortfarande ger en fullgod penetration väljs. Högst svetshastigheten som nås är runt 4m/min med den högsta tillgängliga lasereffekten på 10kW. Några autogena lasersvetsar svetsas för jämförelse.

Svetsförsök med integrerat rotstöd svetsas också.

Svetsförsöken resulterar i två processområden som ger låg porositet i svetsarna. Vid en svetshastighet av ungefär 0,5m/min och lägre fås en svets med låg porositet. Vid svetshastighet av ungefär 4m/min och över, resulterar också i svetsar med låg porositet. Processområdet mellan 0,5m/min och 4m/min resulterar i svetsar med mycket porositet.

Anledning till porositeten är troligtvis nyckelhåls instabilitet.

Svetsar utan full genomträngning visar mycket porositet djupt ner i svetsen, detta är tydligt vid svetsning med integrerat rotstöd.

De flesta svetsar svetsade utan rotstöd hade insjunken topp och för stor rot. Endast svetsar svetsade med den högsta svetshastigheten var inom toleranserna för valda kvalitetsstandarder.

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1 Introduction

Laser Arc Hybrid Welding (LAHW) is a welding process that combines two classic welding processes. The process combines laser welding with an arc welding process. One of the most used combinations is laser welding and Metal Inert Gas (MIG) welding [1], also known as Gas Metal Arc Welding (GMAW). The LAHW process combines some of the advantages characteristics from both processes, for example the deep penetration of laser welding and the joint fit-up tolerances of MIG welding.

Since the introduction of laser power sources for welding applications the price per kW have decreased significantly, about 66% in the last 20 years. [2] This development has brought more interest for the laser welding processes.

Hydro is a global manufacturer of aluminium products. One area being aluminium extrusions. For some applications, the extruded profiles and panels are joined together. The process for joining big aluminium profiles and panels is in many cases today Friction Stir Welding (FSW). FSW both has its advantages and disadvantages in comparison to classic arc welding. One example being that FSW require high forces, both for the clamping of the workpiece and also to perform the joining. [3]

Hydro is interested in the performance of LAHW to be able to evaluate if the processes can be competitive to FSW in some cases.

1.1 Purpose

The purpose of this thesis is to evaluate if LAHW can be a viable alternative to join thicker aluminum profiles. The aim is to LAHW 8mm or thicker extruded aluminum alloys in a butt joint configuration to benchmark the process. Also, a literature review will be performed to gain knowledge of the method.

Questions to be answered by literature review and welding trials:

- What welding speed/productivity are possible to reach, with approved quality?
- Which welding standards are relevant for LAHW?
- Which welding parameters should be used to get a stable welding process?
- What defects are to be expected and how can they be mitigated?
- Is it possible to perform a good quality buttweld without the usage of backing material?

2 Background

In this chapter some background will be presented regarding material characteristics, the welding process, and the quality requirements.

2.1 Aluminium

Aluminium is commonly used in the aviation and transportation industries thanks to its properties as a lightweight material. The reduction in self-weight results in an increased loading capacity. [4]

Another great property of aluminium is that all aluminium is recyclable. The recycling process does not damage the metal and thus aluminium scrap can be recycled repeatedly. However, if the scrap is contaminated, it must be processed for a longer amount of time and in additional process steps. The energy to recycle aluminium is approximately 5% of the amount of energy required for primary production. [5]

One very common product made from aluminium is extrusions. Due to the lower temperature and force needed for extrusion of aluminium compared to steel, aluminium is much more common. The lower temperature and forces put less thermo-mechanical stress on the tools. In general, the temperatures of which aluminium is extruded are lower than the annealing temperature of the tool steels that makes the extrusion die. To extrude aluminium costs less than steel. [6]

Aluminium has good mechanical characteristics and extrusion is a very versatile manufacturing process. Many types of products can be produced through extrusion, often different types of profiles are extruded. Both hollow and open profiles can be extruded. To create big section, panels are extruded and then joined together usually by either FSW or arc welding.

2.1.1 Aluminium alloys

Aluminium comes in many types of alloys and when referring to aluminium it often means aluminium and its alloys. Table 1 shows the numerical designation system according to *Aluminium and aluminium alloys – Chemical composition and form of wrought products – Part 1: Numerical designation system* SS-EN 573-1.

Table 1: Designation of aluminium alloys.

Major alloy elements:	**Aluminum alloy:**
Aluminum 99% or greater	1xxx (1000 series)
Copper	2xxx (2000 series)
Manganese	3xxx (3000 series)
Silicon	4xxx (4000 series)
Magnesium	5xxx (5000 series)
Magnesium and silicon	6xxx (6000 series)
Zinc	7xxx (7000 series)
Other elements	8xxx (8000 series)

The most popular aluminum alloy used for extrusion is the 6000 series and many of these alloys are designed for extrusion. [7]

The major alloy elements and some of their effects is explained below [8]:

- Copper (Cu) increases strength, permits precipitation hardening, reduces ductility, weldability, and corrosion resistance.
- Manganese (Mn) increases strength through solid solution and improves work hardening ability.
- Silicon (Si) increases strength and ductility. Together with magnesium produces precipitation hardening.
- Magnesium (Mg) increases strength and improves work hardening. Solid solution strengthening.
- Zinc (Zn) increases strength, permits precipitation hardening.

Pure aluminum is soft and have low strength. Therefore, aluminum is most often alloyed to improve its mechanical properties. There are four mechanisms of hardening metals:

- Precipitation hardening
- Solid solution hardening
- Cold working
- Grain refinement

Grain refinement or grain size control is not commonly used for hardening aluminum.

Cold working or strain hardening is an important hardening mechanism for alloys that cannot be strengthen by heat treatment. Deformation makes the material stronger and less ductile, which makes for more force to keep deforming the material. If the material is cold worked to much it becomes brittle. If a cold worked piece is heated to the recrystallization temperature the hardening is lost.

Solid solution hardening happens through dissolving an alloy element, or a few, in liquid aluminum and then after cooling the alloy solidifies to a solid homogeneous solution. Depending on the metal and the alloying elements there is a limit of solid solubility where no more alloying elements can be dissolved by the metal before it forms separate phases.

Precipitation hardening or age hardening is created by supersaturating alloying elements and then in a controlled process diffuse into a second phase. An analogy is when solving salt in water, at room temperature water can dissolve a little salt but at elevated temperature it can dissolve much more. If much salt is dissolved at higher temperature, the salt will then precipitate when the temperature drops because the water gets saturated. The same principle is used for precipitation hardening. The temperature gets raised enough to for the aluminum to solve the alloying elements in a single phase. Then the temperature is lowered fast with a high cooling rate, often by quenching in water. This makes the solution super-saturated. The cooling rate needs to be fast enough so that a second phase does not have time to be formed. The then super-saturated solution is aged, which stimulates the precipitation of particles of a second phase in a controlled manner. The ageing is performed by controlled heating to a specific temperature at which the atoms start to diffuse, and a very fine precipitation begins to form. Both the temperature and time is important factors, to high temperature and/or to long time makes for an over aged material with the size of the particles being too big and less disperse. Some alloys harden at room temperature, known as natural ageing, when heating the alloy, it is called artificially aged. Precipitation hardening gives a higher strength compared to solution hardening but reduces the ductility of the alloy. [9]

The non-heat treatable alloys are:

- Pure aluminum, 1000 series.
- Aluminum-manganese, 3000 series.
- Aluminum-silicon, 4000 series.
- Aluminum-magnesium, 5000 series.

The heat treatable alloys are:

- Aluminum-copper, 2000 series.
- Aluminum-magnesium-silicon, 6000 series.
- Aluminum-zinc-magnesium, 7000 series.
- Other, 8000 series.

The condition of the aluminum alloys is described in a suffix after the numbers, e.g., 6061-T6. The “T” describes the condition and the number “6” specifies the process. There are five basic designations [8]:

- F – as fabric. There is no specification or control of the amount of strain hardening or heat treatment.
- O – annealed. Lowest strength. The O can be followed by a suffix to describe the specific heat treatment.
- H – cold worked. “H” is followed by at least two digits to describe the amount of cold working or any heat treatment that could have been used.
- W – solution heat treated. Used for alloys that precipitation hardens at room temperature (natural ageing). “W” if followed by a time indication for the natural ageing period, e.g., W 3h.
- T – thermally treated. The alloy is aged, and the ageing is specified by one or more numbers that follows the “T”.

2.1.2 Welding characteristics of aluminum

There are a few characteristics of aluminum that makes fusion welding more challenging than steel. The characteristics are:

High heat conductivity

Aluminum has a high heat conductivity, three times as high as steel [10]. The high heat conductivity makes for more energy to weld, the heat gets transported away into the material. It is more beneficial with welding processes with high energy density for welding aluminum.

High coefficient of thermal expansion

In comparison to steel, aluminum has roughly twice the coefficient of thermal expansion. This makes for greater distortion because of the heat cycles when welding. Using welding processes with higher energy density makes for less distortion. [10], [11]

Substantial difference in hydrogen solubility of solid and liquid aluminum

There is a significant difference in solubility of hydrogen between solid aluminum and liquid aluminum. Liquid aluminum can dissolve more hydrogen than solid aluminum. This can affect welding by pores of entrapped hydrogen. Entrapped hydrogen gas can easily create pores due to the solidifying of the melted pool created by the welding process. The hydrogen gas might not have the time to evaporate away from the melted pool before it solidifies. [11], [12]

Layer of aluminum oxides on the surface

Aluminum has a high affinity to oxygen leading to the formation of an oxide layer of Al_2O_3 on the surface of the material. The oxide is thermally stable, non-conductive and has a melting temperature of 2050°C while aluminum alloys have a melting temperature of around 570°C. The oxide contributes to including a higher risk for incomplete fusion. [10], [11]

High surface reflectivity

Aluminum alloys have a high reflectivity and therefore, when laser welding, the laser beam should be oriented at a slight angel to reduce the risk of back reflections. Back reflections can damage the laser equipment. [13]

2.1.3 Filler materials

Over 85% of all filer materials used for aluminium welding are of the types 4043 or 5356. [14]

When welding aluminium alloys, the filler material often does not match the base material on all its characteristics. The most crucial characteristics of aluminium alloys are chemical composition, mechanical properties, appearance, and corrosion resistance. Often some of the characteristics must be prioritised. Beyond mentioned characteristics other aspect also must

be included e.g. crack resistance, colour match, the response to anodising, and creep resistance. [8]

There are a few general guidelines when choosing filler material for welding of aluminium alloys. The points are mostly accurate regarding welding of the 5000- and 6000 series. [8], [14] :

- If the base material contains more than 2-2,5% magnesium, use 5356 filler material. If the base material contains less, 4043/4943 or 5356 can be used.
- When good anodizing colour is a requirement use 5356.
- 5356 should be avoided if the service temperature exceeds 65°C due to the risk of stress corrosion. Use filler material with less than 3% magnesium instead.
- 5356 gives higher toughness and ductility than 4043/4943 and therefore increases the resistance to crack propagation.
- For better aesthetic appearance use 4043/4943. The welds are brighter and generally much smother.
- 5356 is twice as stiff as 4043/4943 and therefore has better feed ability through the welding machine and welding gun. Due to the relative softness of aluminium, it can be a problem to feed the wire and with softer alloys there is a greater risk of the wire getting tangled in the equipment.

In different welding standards there are sometimes tables which recommend filler materials. An example is in annex B in *Welding – Recommendations for welding of metallic materials – Part 4: Arc welding of aluminium and aluminium alloys* SS-EN 1011-4. In many tables with recommendations of filler materials there are often a few choices depending on what properties that are of importance. For example, the first alternative has closest mechanical properties to the base material and so on.

2.1.4 Welding of 6000 series alloy

The 6000 series has some specific challenges when to be welded. One is the risk of hot cracking. Hot cracking is a collection of high temperature cracking mechanisms that have a few different types: solidification cracking and liquation cracking. All aluminium alloys have some problem regarding hot cracking but depending on the chemical composition the risk is either higher or lower. The risk of hot cracking in the 6000 series is considered very high if the welding is performed without filler material (autogenous welding) or with a high dilution

of parent material in the weld. To mitigate the problem the 6000 series should be welded with filler material and preferably with high amount of dilution of filler material in the weld. 4043/4943 filler material reduces the risk hot cracking, 5356 filler material has a slightly higher risk for hot cracking than 4043/4943. [7], [9]

Due to the heat cycle of welding, a loss of hardness and strength happens. In the heat affected zone (HAZ) close to the weld, there are areas that experience over ageing due to the heat cycle. The loss of strength in the 6000 series are higher for artificially aged metal than in naturally aged. A lower heat input reduces the amount of over ageing and the area it concerns. [8]

When arc welding there is always a loss in strength and hardness. The amount of loss is described in Eq. 1

$$r = \frac{R_m^{\text{weld}}}{R_m^{pm}} \qquad \textit{Eq. 1}$$

Where:

R_m^{weld} is the lowest ultimate strength post welding.

R_m^{pm} is the ultimate strength of the parent material.

r is the reduction factor.

A typical r-value for arc welding 6000 series alloys are between 0,6 to 0,8. [15]

2.2 Laser Arc Hybrid Welding

The laser arc hybrid welding that has been done for this thesis are a combination of laser welding and MIG welding. Some important parameters and characteristics of the separate processes will be presented in the following chapters. The LAHW chapter presents the parameters and different setups specific for LAHW.

2.2.1 Laser welding

When laser welding, a laser beam is created and is used to weld with. There are different types of laser power sources and depending on the type, different wavelengths and power can be achieved. Metals absorb different amount of energy depending on the temperature of the material and the wavelength of the laser, for instance aluminum has high reflectivity, especial for longer wavelengths and therefore it is more effective and easier to use a laser power

source with shorter wavelengths. As an example, a CO_2 laser has a wavelength of about 10,6µm, which is considered long while a fiber laser has a typical wavelength of around 1,075µm (depending on which medium used to create the laser beam). Therefore more energy is absorbed from the fiber laser compared to the CO_2 laser. [13], [16]

A laser welding process consists of a power source, transportations system for the laser beam and the optics. As mentioned earlier, there are different types of laser power sources, and the most common for laser welding are gas-, diode- and solid-state lasers.

The transportation of the laser beam is usually done by either mirrors or a fiber depending on the power source. A CO_2 laser power source uses mirrors to guide the laser beam and solid-state power sources uses fibers to guide the laser beam to the laser optics. [17]

Figure 1 shows the optics for a solid-state laser with an optic fiber guiding the laser beam to the optics.

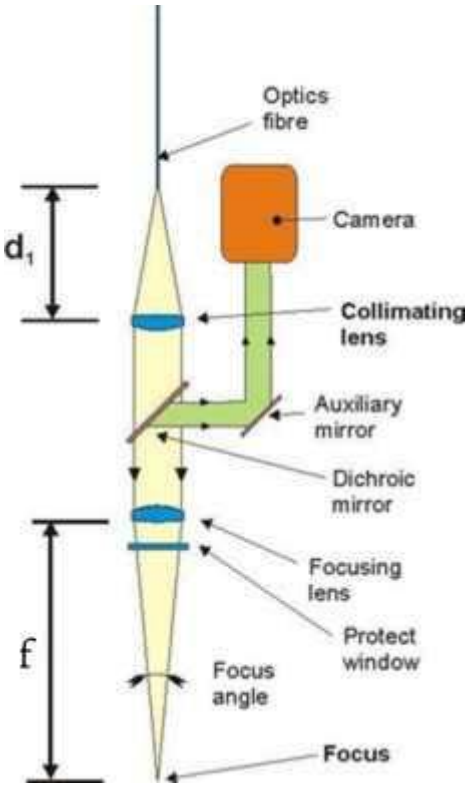


Figure 1: Optical system for a solid-state laser welding machine. [17]

The shape of the laser beam is not exactly as a X-shape but more like an hourglass, see Figure 2. Also, the energy in not linearly distributed over the beam profile but have rather a Gaussian beam shape. d_0 is the spot size and f is the focal distance.

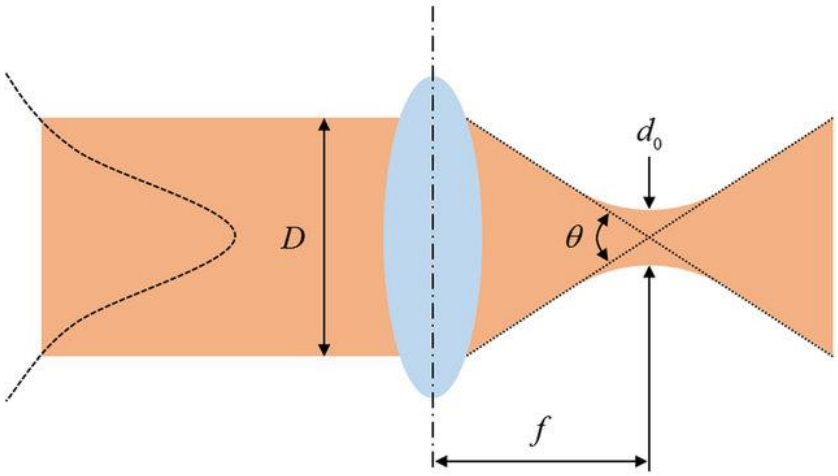


Figure 2: Gaussian beam propagation with focusing lens. [18]

Two types of welding are used when laser welding, heat conduction mode welding and keyhole welding. Conduction mode welding is often used to weld thinner material and have a shallow penetration. Keyhole welding is used for deep weld penetration and is the most common when LAHW.

High power density is required for keyhole welding with laser. The laser beam creates such high temperature in the material vaporizes creating an overpressure. The pressure creates a hole around the laser beam. An equilibrium is needed by several parameters to be able to keep the keyhole open and stable, surface tension of the melt, the vapor pressure, and the hydrostatic pressure are some of the most important. When a keyhole is created the laser beam then gets reflected many times by the walls of molten metal. The molten metal has much higher absorption of the laser beam and therefore when the keyhole is established, the problem of high reflectivity is reduced. [13]

Keyhole welding produces a very deep and narrow penetration, also at high welding speed. The distortions are low due to a narrow heat affected zone.

There are a few problems that are common for keyhole welding, one of them is random collapse of the keyhole which often leads to porosity. [13]

Figure 3 shows a schematic picture of how the behavior of the keyhole, how porosity can be created and its dependence on different parameters such as welding speed and laser power. At low welding speed the keyhole is not stable, which can more often lead to collapse, and the melt flow has a negative effect on the porosity. With higher weld speed and higher laser

power the keyhole gets more stable, and the melt flow gets more beneficial which results in lower amount of porosity. [19] Figure 4 shows the keyhole welding with a laser beam.

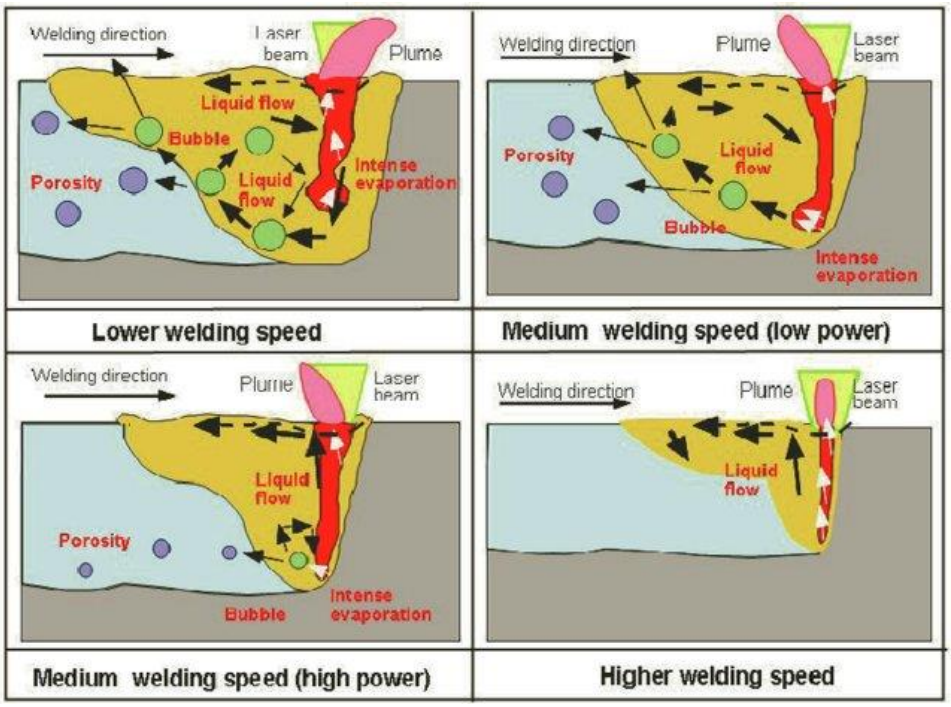


Figure 3: Schematic representation of plume-, keyhole behaviour, melt flows and bubble generation leading to porosity [19]

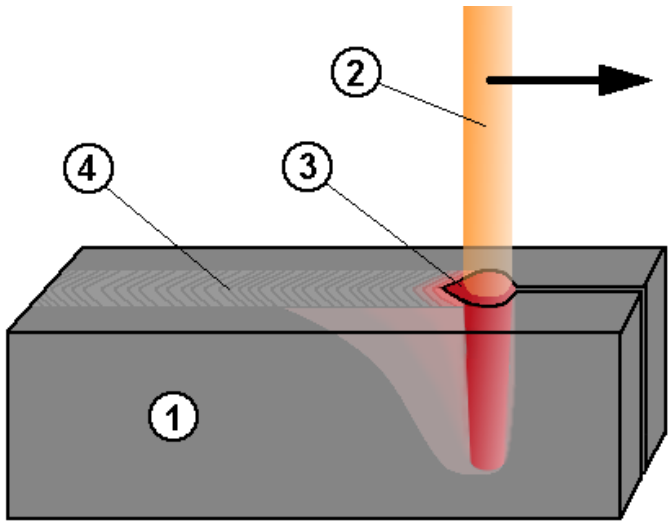


Figure 4:Keyhole welding with laser beam, 1 base material. 2 Laser beam. 3 Keyhole. 4 Weld. [20]

As seen in Figure 4, the deep end of the weld pool is narrower than the top. The gas pores created deeper in the weld have less time to evaporate before the solidification of the weld because the area of molted metal is smaller than in more shallow areas.

2.2.2 Metal inert gas welding

MIG welding is considered a classic arc welding process. MIG stand for Metal Inert Gas and is GMAW (Gas Metal Arc Welding) with an inert gas as the shielding gas. When welding aluminum, an inert gas is used; argon or helium or a mixture of the two. For welding of steel an active gas mixture is used, MAG (Metal Active Gas). [21]

MIG welding is a semi-automatic or automatic welding process where a filler wire is fed continuously when welding. The filler wire pass through an electrode, the contact tube, and then the filler wire acts as both an electrode and filler wire. Figure 5 illustrates the MIG welding process.

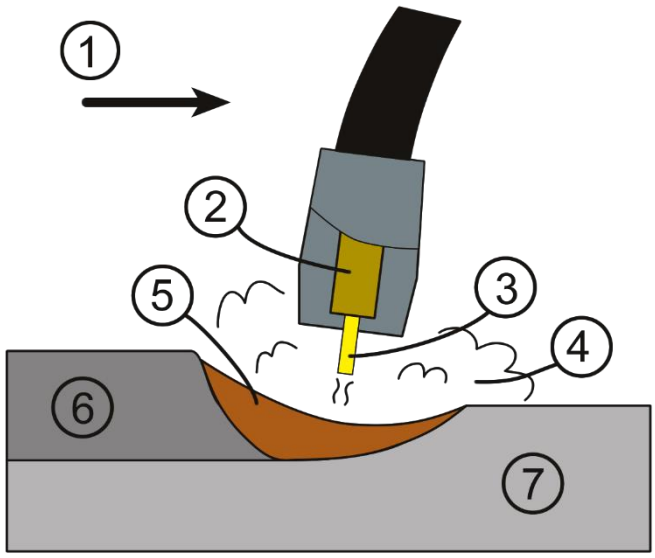


Figure 5: Schematic figure of the MIG welding process. 1 Direction of welding, 2 contact tube, 3 filler wire, 4 shielding gas, 5 weld pool, 6 weld, 7 base materials. [22]

When welding aluminum, the most common polarity is DC (direct current), electrode positive. There are three basic ways of metal transfer for the MIG process. Short circuit, globular and spray. The ones used for aluminum welding are short circuit and spray. Figure 6 shows the different metal transfer modes, including a fourth mode, pulse.

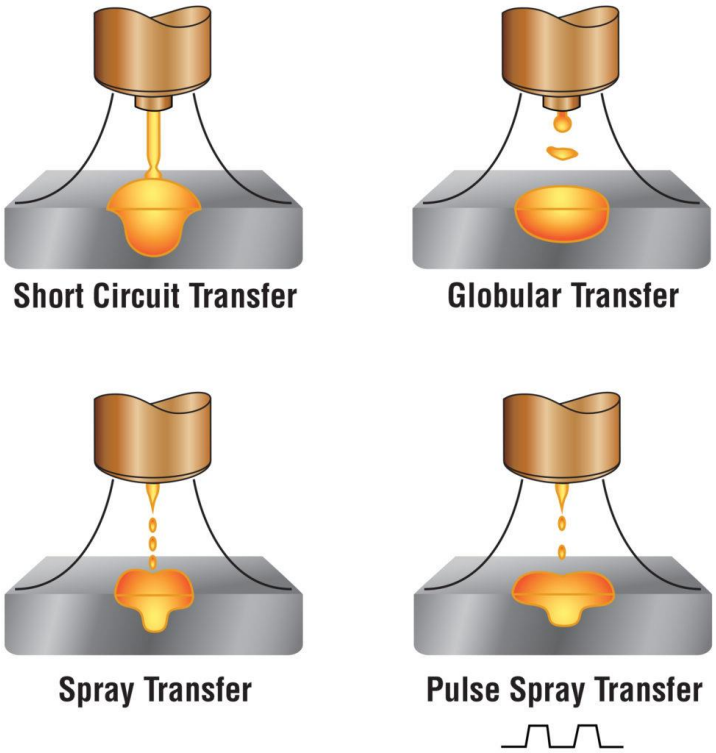


Figure 6: The four main metal transfer modes for MIG welding. [23]

A simple way to describe the metal transfer modes are that in short circuit welding the filler wire is feed down, hits the material/weld pool and then a bit of the filler wire melts off. In spray mode, the wire does not hit the melt surface and the current is so high that the filler wire is melted and sprayed down as small droplets to the material. Spray mode requires high current and therefore it creates much more heat than short circuit welding. However, it is not as violent of a process as the short circuit and therefore it does not create any or little spatter. Due to the burn off from filler wire, short circuit welding creates a lot of spatters. Spatter is molten material that hits the surface outside the weld area.

In this thesis two advanced types of the metal transfer modes will be used, Cold Metal Transfer (CMT) and pulsed welding. CMT is a type of short circuit, cold welding process that is developed by Fronius. CMT is an advanced welding technique that is using reciprocating wire feeding. [21]

Most new power sources work with different synergies. The user enters a few parameters into the welding machine, e.g., thickness of the filler wire, thickness of the material that should be welded, shielding gas and then the machine has a program that adjusts and set the welding characteristics. The welding machine has some preprogramed synergies and in a few advanced machine new synergies can be downloaded from the manufacture of the machine. Depending on the machine model, metal transfer mode and manufacturer of the machine,

there are a few parameters that can be changed in the synergy. The usage of synergies reduces the number of parameters that the operator has to control, “one knob” controlling. [24]

Both CMT and pulse mode uses synergies. The processes will be briefly explained, and the adjustable relevant parameters mentioned.

CMT

The process can be simplified as a process where the filler wire is dipped in the melt pool to transferee a droplet under no current. When the wire is retracted, the arc is once more established, and the cycle repeated. This makes for a shorter period of heat input. Welding with CMT reduces the amount of spatter compared to regular short circuit welding. [25]In Figure 7 the steps of CMT welding are shown and explained.

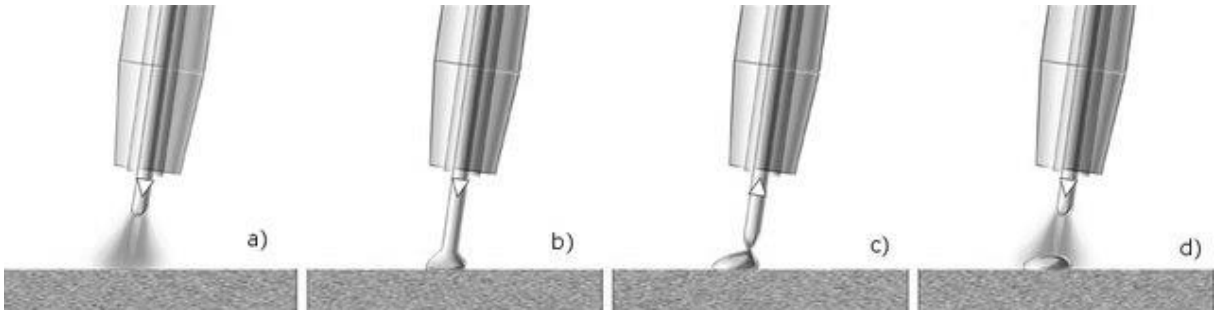


Figure 7: CMT process. (a) arcing period, filler wire moves towards the weld pool. (b) Filler wire dips into the weld pool and the arc extinguishes. (c) Filler wire moves backwards, and the droplet detaches. (d) repeating of the cycle. [26]

Thanks to advanced and accurate digital process control, the welding machine can detect the short circuit and withdraw the wire which interrupts the arc. This happens with high precision and very high frequency. Heat is only introduced briefly in the arcing period and that is one reason that the welding process generates very low heat.

There are different manufactures with different solution on how to retract the wire with the required accuracy and speed, when using a reciprocating wire feeding welding process. Fronius uses a two-wire drive system, the main wire feeder continuously feeds wire and a small motor in the handle controls the rapid forward and backward movement of the wire. A flexible buffer is between the motors in the hose. [21]

Pulsed welding

Pulsed welding is a type of forced spray welding. The pulsed welding process utilizes a low background current that is sufficient to maintain an arc but not high enough to melt off the

filler wire. On the background current a high current pulse is superimposed, a peak current. Under the right conditions this causes one single droplet of molten filler wire to be transferred to the weld pool by a spray transfer. Therefore, it is possible to achieve a spray transfer, stable arc and a lower average welding current, than for regular spray transfer mode. Figure 6 show the pulse welding with the varying current, back current and peak current. Pulsed MIG welding has a frequency of around 30-300 Hz. The penetration of pulsed welding is less than for regular spray transfer. [21], [27]

Parameters that usually are set when using pulsed MIG welding are the same as for CMT, the synergy program then adjust the rest of the parameters.

There are a few correction parameters that can be used depending on the circumstances and some of them are:

- Arc length correction, which is used for modifying the arc to shorter or longer arc length.
- Droplet detachment correction, when pulse synergic welding, the droplet detachment force can be adjusted. Lower- or higher droplet detachment force. When CMT welding, the boost current is adjusted to increase or decrease the heat input to the base material.
- Dynamic correction is used during CMT welding for influencing the short-circuiting dynamics. Harder and more stable arc or softer arc and less spatter.[28]

2.2.3 Laser arc hybrid welding process

Laser arc hybrid welding is a process where two processes are combined, laser and an arc welding process. The most common is hybrid welding with laser and MIG processes, but there is other configuration with other arc welding processes. The different welding configurations are laser-MIG, laser-TIG (Tungsten Inert Gas) and laser-plasma arc. [29]

As mentioned earlier the most common is laser-MIG and that is the configuration that is used for this thesis.

When combining the two welding processes for LAHW, advantages from both processes can be utilized. At the same time some negative factors from the processes are reduced. As an example, laser beam welding has very good penetration, but the process requires tight

tolerances between the pieces that should be welded together, because of the narrow beam. Adding the MIG process, which has good gap bridging capabilities, the LAHW process still has the good penetration from the laser beam but at the same time allows for welding joints with bigger gaps than for only laser beam welding. [29]

In LAHW there are many settings, both connected to the separate welding processes but also a few that is specific for LAHW. In Figure 8 an illustration of LAHW is shown. Figure 8 shows an arc-leading welding setup. If the laser is in in front, it is called laser leading. LAHW with leading arc or leading laser gives different characteristics to the weld bead, a further explanation will be given in chapter 2.4.

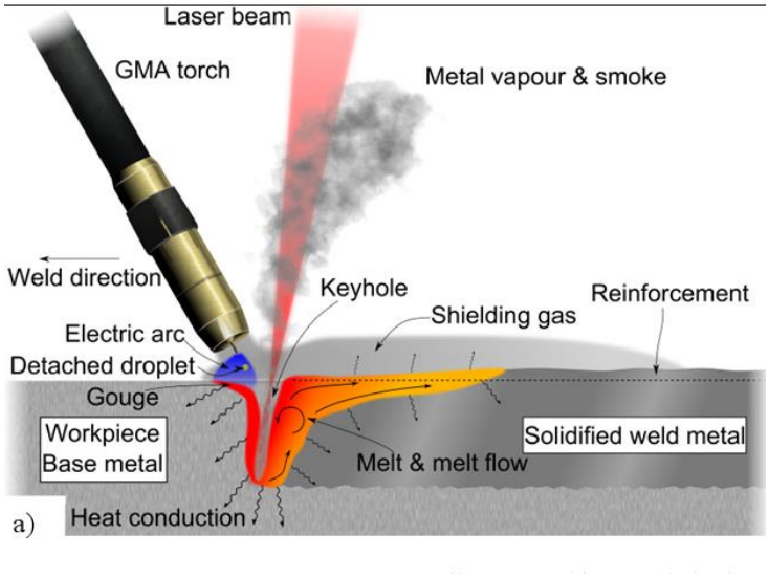


Figure 8: Illustration of LAHW [30]

Figure 9 shows a closer look of the geometry of the setup. Table 2 shows the parameters and their notation, based on Figure 9.

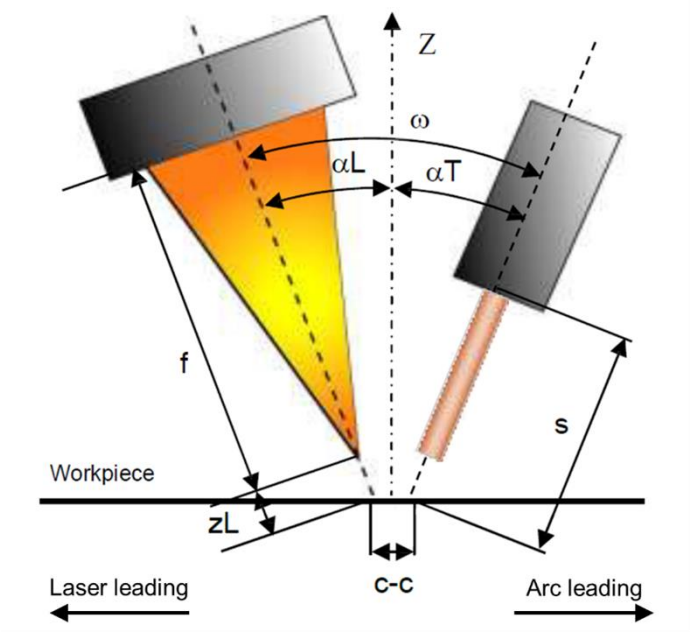


Figure 9: Schematic illustration of the welding head from a side view with the notations used in the report. [31]

Table 2: Parameters and notations related to the ones shown in Figure 9.

Parameter	**Notation**
Contact to work piece distance (mm)	s
Set-up angel (°)	ω
Wire angel (°)	αT
Laser angel (°)	αL
Heat source distance (mm)	$c - c$
Focal point off-set (mm)	zL
Process orientation	Arc leading or Laser leading

As seen from Table 2, there are many parameters and settings to be optimized for LAHW. Besides the parameters and settings in Table 2 there are the additional parameters for each of the two welding processes. It can be very difficult and time consuming to optimize all the parameters to get high productivity and necessary quality. [32]

Many of the parameters mentioned above is related to what is part of a welding procedure specification according to the standard *Specification and qualification of welding procedures*

for metallic materials - Welding procedure specification – Part 6: Laser-arc hybrid welding, ISO 15609-6.

2.3 Quality and productivity requirements

In this chapter a few of the standards regarding FSW and LAHW will be mentioned. FSW productivity for welding extruded panels will be presented.

2.3.1 FSW quality and productivity

In most cases of FSW of extruded profiles and panels, the quality requirements are class C according to *Friction stir welding – aluminium – part 5: quality and inspection requirements*, ISO 25239-5. Due to the flexibility of the extrusion process, many types of products to different costumers can be manufactured. Depending on the costumer and product application there can also be specific requirements for instance regarding the surface quality which might demand machining or preparation for painting.

Not all joints are suitable or can be welded with FSW, therefore some amount of arc welding will often be required. Same as for FSW, the quality class C is most often applied, but the standard is *Welding – Arc-welded joints in aluminium and its alloys – Quality levels for imperfections*, ISO 10042.

The welding speeds that can be used for long length FSW (long panels of profiles that are joined together) are approximately:

- 3-3,5 m/min for 4-6mm thickness
- 1-2 m/min for 6-10mm thickness
- 0,5-1 m/min for 10-15mm thickness

Which type of alloy in the 6XXX series also affects the welding speed. [33]

2.3.2 Standards for laser arc hybrid welding

There are a few standards for LAHW. The most relevant welding standard is *Welding and allied processes — Process specification for laser-arc hybrid welding for metallic materials*, ISO 23493. The standard gives recommendations for welding including joint preparation and welding parameters.

For LAHW in steel, nickel and nickel alloys there is a standard for quality levels, *Welding – Laser-arc hybrid welding of steels, nickel and nickel alloys – Quality levels for imperfections*, ISO 12932. However, no equivalent standard exists for LAHW of aluminium at the time of writing this thesis. An alternative method to verify the quality, is to verify the upper surface

and the upper weld volume to an arc welding standard and the deeper penetration volume and the root of the weld according to a laser welding standard.

The standard for the upper surface quality is *Welding – Arc-welded joints in aluminium and its alloys – Quality levels for imperfections*, ISO 10042

Relevant quality for laser welding, for the lower part of the weld: *Electron and laser-beam welded joints – Requirements and recommendations on quality levels for imperfections – Part 2: Aluminium, magnesium and their alloys and pure copper*, ISO 13919-2.

The reason for the two different standards is that the laser process mainly does the deep penetration welding which affects the inside and the root of the weld. The MIG process primarily affects the upper surface.

Currently no standard regarding welding procedure qualification is available for LAHW of aluminium. However, there is one for steels, nickel and nickel alloys, *Specification and qualification of welding procedures for metallic materials – Welding procedure test – Part 14: Laser-arc hybrid welding of steels, nickel and nickel alloys*, ISO 15614-14.

In a standard that has been mentioned before, *Specification and qualification of welding procedures for metallic materials - Welding procedure specification – Part 6: Laser-arc hybrid welding*, ISO 15609-6, there is stated an equation for the heat input. The equation is shown in Eq. 2

$$Q_{\text{nom}} = \frac{(P + U * I)}{v} 10^{-3} \qquad \textit{Eq. 2}$$

Q_{nom} is the nominal heat input, in kilojoule per millimeter.
P is the laser power in kilowatt.
U is the arc voltage in volt.
I is the welding current in ampere.
v is the travel speed in millimeters per second.

2.4 Welding parameters and its effects

In this chapter a few of the parameters and common problems of LAHW and their impact, according to some scientific papers, will be presented. The information will work as tools during the welding trials. Parameters and problems are not presented in any order of importance.

2.4.1 Leading laser and leading arc

I. Bunaziv et al. presented that a leading arc configuration produces a deeper penetration than for leading laser. I. Bunaziv et al. proposed a theory that the arc preheats the material and therefore the material absorbs more of the laser beam. [34] Leading arc seems to give more spatter and the weld tends to be more narrow. [34]

However, in a paper by G. Casalino et al. shows the opposite result, leading laser has more penetration than leading arc. Other thing to notice in this paper is that the arc process was TIG with high frequency DC current, which might influence the results. In the paper the leading laser gives less porosity than the leading arc. [35]

2.4.2 Power of the arc

The welding current of the arc seems to have negligible effect on the penetration of the weld, as mentioned before the laser beam is the process that gives the deeper penetration. But a few papers have shown that, when having leading laser, higher weld current reduces porosity. One theory is that with higher current, the melted weld pool gets bigger and longer, and thus, the solidification takes longer giving hydrogen more time to escape the melt pool. [36]

2.4.3 Type of mode for MIG welding process

Earlier two types of MIG welding modes have been briefly explained, pulsed welding and CMT. CMT is a “cold” process and has lower heat input in comparison to the pulse mode. X. Han et al. proposed in a paper that it is possible to get good solid, low porosity laser arc hybrid welds with the use of both modes. Since CMT runs with lower heat input it gives a smaller heat affected zone of the material and higher tensile strength than when using pulse mode with the higher heat input. CMT seems to give less spatter than when welding with pulse mode. [37]

2.4.4 Type of shielding gas

Most used types of shielding gas are argon, helium, or a mixture of them both. There are some differences of how much of an influence helium have on the LAHW process.

A few papers showed that with a higher helium content the penetration depth increases and that the porosity defects were reduced. [38], [39] Some papers indicates less or non-benefits

of the addition of helium. Due to the high cost of helium, the usage is not suitable for most applications. [34]

2.4.5 Welding speed

The welding speed is one of the parameters with the most effect on the weld quality. LAHW speed can in a few cases be higher than when laser welding. [11], [40]

The welding speed is, as many other welding parameters, influenced by other parameters. With welding speeds of up to 6,5 to 7 m/min good quality welds of 5mm thick aluminum has been welded. [41] Too high welding speed can result in porosity due to the faster solidification rate of the melt pool and reducing the welding speed can mitigate the problem. [42]

However, S. Katayama et al. has shown that increasing of weld speed can reduce the porosity tendency. [43]

To be able to produce high quality welds using LAHW finding a balance between the arc power, laser power and welding speed is important.

2.4.6 Heat source distance

The distance between the arc and the laser beam must be in a certain interval to get a stable welding process and to get the benefits from both processes and the synergic effects of them. If the distance is too short, there is a risk of the arc affecting the keyhole so that becomes unstable and the risk of intermittent closure of the keyhole increases. If the heat source distance is too far, the LAHW process will become two different processes and the synergic effect will be lost. [34] For LAHW on aluminium optimal heat source distance is reported to be 2-4mm. [43]

2.4.7 Porosity

There are some general and specific ways to try to mitigate the problem of porosity when using LAHW for aluminum. A few of the welding parameters and their influence on porosity have already been mentioned but additional parameters are presented below.

As in some of the parameters above there is not always a clear answer to how, why and if the modification to a parameter will work. Conflicting evidence of different parameters creating different results have been found in the literature.

It is widely known that it is of significant importance to have clean material when welding, especially aluminum. It is also a known fact that one reason for porosity in the weld is the contamination due to improper cleaning, both because of not good enough cleaning and/or the usage of the wrong type of cleaning which can results in leftover residues. Another reason is moister on the surfaces that contaminates the weld. The filler material must also be clean. [44]

In table A.1 in *Welding – Recommendations for welding of metallic material – Part 4: Arc welding of aluminium and aluminium alloys,* ISO 1011-4 there is examples of reasons and counter measurements to reduce porosity.

A few methods can be used to remove the oxide layer from the surface on aluminum. One of the most used methods is to brush the surface with a stainless-steel brush, but studies have shown that it just smears around the oxide layer and dirt instead of removing it. [45] If the oxide lays are not removed, it can result in higher porosity in the weld and the risk of incomplete fusion of the weld. After cleaning and removal of the oxide layer, the oxide layer will instantly appear again therefore it is recommended that welding should be performed soon after. A thinner oxide layer is better than a thicker and the oxide layer thickens by time. The principal applies to filler material as well, the filler material should be used not to long after it has been opened. [9], [45]

When having high demands of the weld quality, the oxide removal becomes more important. Some of the best methods with best results are chemical pickling or laser ablation. These methods are more expensive, demands more equipment and, for pickling, handling of strong, environmental hazardous and dangerous chemicals. [46]

The influence of gap width when buttwelding is not certain. One paper says it does not affect or have a small effect on the porosity. [42]

Generally, the LAHW process can produce good quality welds when having a gap of around 5% to 10% of the material thickness or the root face. In Table 2 in *Welding and allied processes — Process specification for laser-arc hybrid welding for metallic materials,* ISO 23493, there is recommendations for joint preparations for single sided welding. As an example, there is recommendations for the root gap when having and I-joint or a V-joint.

As mentioned earlier, the welding speed is a crucial parameter and has both an influence on and are influenced by many other welding parameters. The welding speed must be in the correct range, otherwise it can create porosity in the weld.

The purity of the shielding gas must be high, otherwise it can affect and increase the porosity of the welds. Another important aspect is to have right type of gas hoses and fittings. The gas hoses must keep moister out, in some material the moister can get through and then condense on the inside of the hose and then enters the weld together with the shielding gas. Fittings can also leak in moister to the gas system. If there is a problem with a lot of porosity it is important to control the shielding gas quality and the gas system. [9]

The flow of the shielding gas is also important. Too high flow rate can create turbulence that bring moister and air into the weld puddle while a low flow rate will not protected the melt pool efficiently. [9]

A gas flow of 12-30 l/min is recommended in *Welding and allied processes — Process specification for laser-arc hybrid welding for metallic materials,* ISO 23493.

The recommended gas flow rate also depends on what type of shielding gas that is used. With pure helium or a gas mixture of argon/helium a higher gas flow will be required, due to the lower density of helium.

In deep welds of aluminium a forward inclination of the laser beam might help to reduce the porosity. [47]

Porosity in aluminium welds can be divided into two groups, hydrogen induced pores and process induced pores. Porosity because of hydrogen have been mentioned in section 2.1.2. Hydrogen induced pores are often much smaller than process induced pores and they have a spherical shape. The process induced pores are often larger and have an unregular shape, often the shape is like an elongated hole. Process induced pores is a result of a collapse of the keyhole which then traps gas in the melted aluminium which subsequently solidifies to a pore. The process induced pores is located in the centre of the weld, in the area where the keyhole travels. [48]

The characteristics of the metal transfer might influence the keyhole stability and therefore process induced pores. Short circuiting and big droplets might disturb the keyhole and make it more prone to collapse. To mitigate the problem, it is suggested to raise the amperage which change the transfer mode towards either spray or if using pulse, the risk of short circuiting is reduced and the size of the droplet is reduced. [49]

2.4.8 Sagging of the weld

One common issue when buttwelding aluminum is the risk of sagging of the weld, especially at the root. Due to both the high thermal conductivity and the low viscosity of the weld pool aluminum has a narrower process area than steel for having a good weld root. [14]

The most common way to mitigate the problem is to have a backing material. The backing material can either be removable or nonremovable. A nonremovable backing material is often made of the same alloy as the base material and will be integrated into the construction. Removable backing material can be made from copper or stainless steel, the backing material does not melt or weld but help keeping and forming the weld root. [50]

V. Geert suggests that to minimize the problem of sagging of the root, the welding should be performed out of position. Out of position means not welding in the PA position according to *Welding and allied processes – Welding positions,* ISO 6947. PA position means flat position. Positions that reduce the risk of sagging is PC, horizontal position, and PF, vertical position welding upwards. [51]

2.4.9 Compilation of parameters and frequent problem

Table 3 shows a brief compilation of the parameters, problem, and their effects.

Table 3: Compilation of parameters, problems, and their effects.

Leading laser	Might create less porosity,
Leading arc	Might have deeper penetration,
Heat source distance	Optimal distance is 2-4mm, affects the stability of the process and might affect porosity,
Shielding gas	Pure argon, addition of helium might reduce porosity.
Metal transfer mode	CMT seems to give less spatter. Pulse gives higher heat input.
Welding speed	Welding speed is highly affected by the arc and laser power. Must be right to get a stable process.
Power of the arc	No major effect on the penetration. In leading laser higher arc power might reduce porosity.
Porosity	Widespread problem when welding aluminum. Important to have clean material. Many welding parameters can influence porosity. Porosity can be divided into two groups, hydrogen induced pores and process induced pores.

3 Experimental

In the following chapter the material, the equipment, the set-up, and the welding trails will be explained.

3.1 Base material

The base material that is used in the welding trials are from the 6000 series aluminium alloys, more specifically: AW6082-T6 Chemical compositions according to *Aluminium and aluminium alloys – Chemical composition and form of wrought products – Part 3: Chemical composition and form of products,* SS-EN 573-3. is given in table Table 4.

Table 4: Chemical composition of the base material used for welding tests.

Alloy	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Al**
EN AW 6082	0,7-1,3	0,5	0,1	0,4-1	0,6-1,2	0,25	0,2	0,1	Balanced

The sizes of the weld coupons are approximately 250x80 mm and were welded together in pairs along the 250mm length. A picture of a piece of material is shown in Figure 10. The thickness of the material is 8mm.

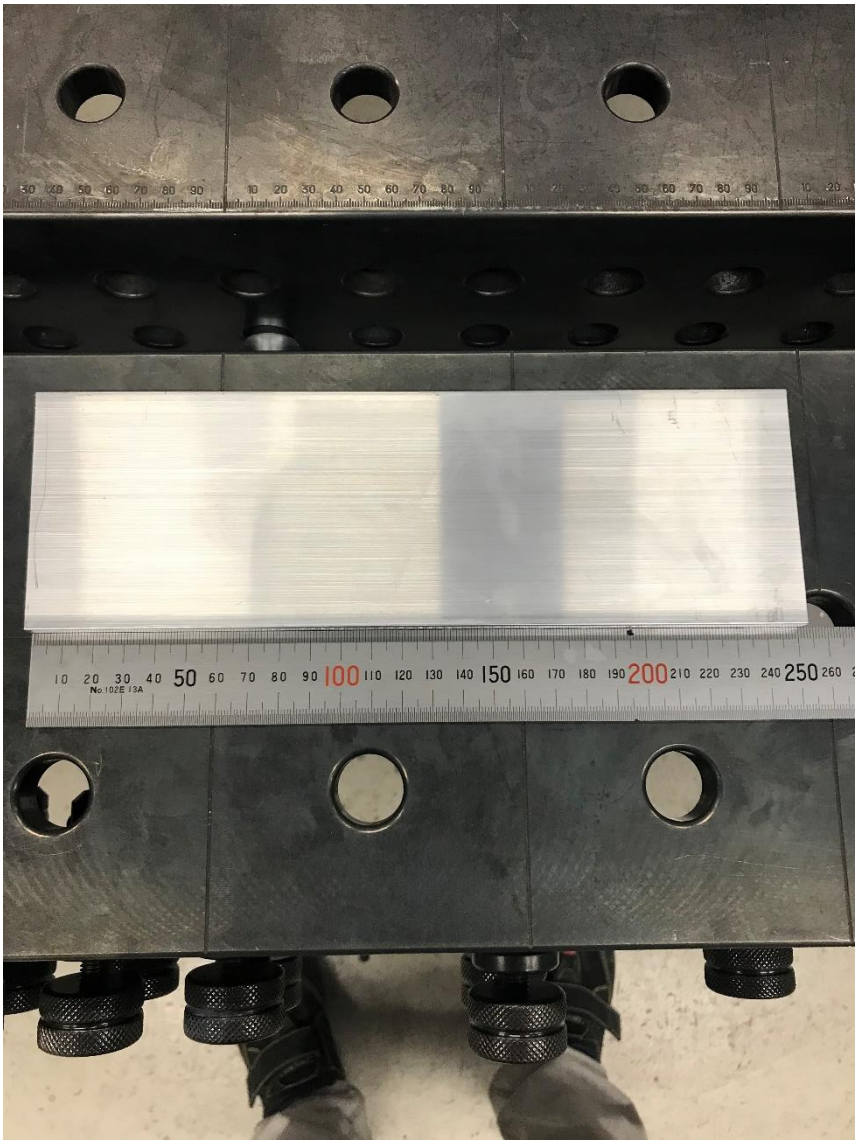


Figure 10: Base material, 6082-t6 alloy used for welding tests.

3.2 Filler wire

The filler wire that is used in the welding trials is of type 5356. The chemical composition of 5356 is seen in Table 5 below. The filler wire is 1,2mm in diameter.

Table 5: Chemical composition of filler wire 5356. [52]

Mn	**Si**	**Cr**	**Al**	**Cu**	**Fe**	**Mg**	**Zn**
0,13	0,05	0,12	94,56	0,01	0,13	4,9	0,01

3.3 Laser, arc welding and robotic equipment

The equipment used during the LAHW trials is shown in Table 6.

Table 6: Laser, robot and arc welding equipment

Robot	6 axis ABB IRB 6700-155/2.85 IRC5 Controller
Laser source	IPG YLS-10000-S4-Y17 10kW Fiber laser, 1070nm wavelength
Optics	Permanova WT04 Motorized focusing unit, -6mm to +25mm
Collimator lens	f=180 mm
Focus length	f=250 mm
Fibre diameter	400 µm
Spot size	0,56 mm (at focus)
Arc welding power source	Fronius CMT 4000 Advanced and FroniusTPS 400i
Welding torch	Robacta Drive CMT

3.4 Welding set-up

Figure 11 shows a picture of the welding head. In Table 7 the used values of the parameters are shown, the notations are according to Figure 9.

Table 7: Welding parameters and values used in the welding trials.

Parameter	**Notation**	**Used values**
Contact to work piece distance (mm)	s	15-20
Set-up angel (°)	ω	45
Wire angel (°)	αT	35
Laser angel (°)	αL	10
Heat source distance (mm)	$c - c$	3-5
Focal point off-set (mm)	zL	0
Welding direction	Arc leading or Laser leading	Both directions

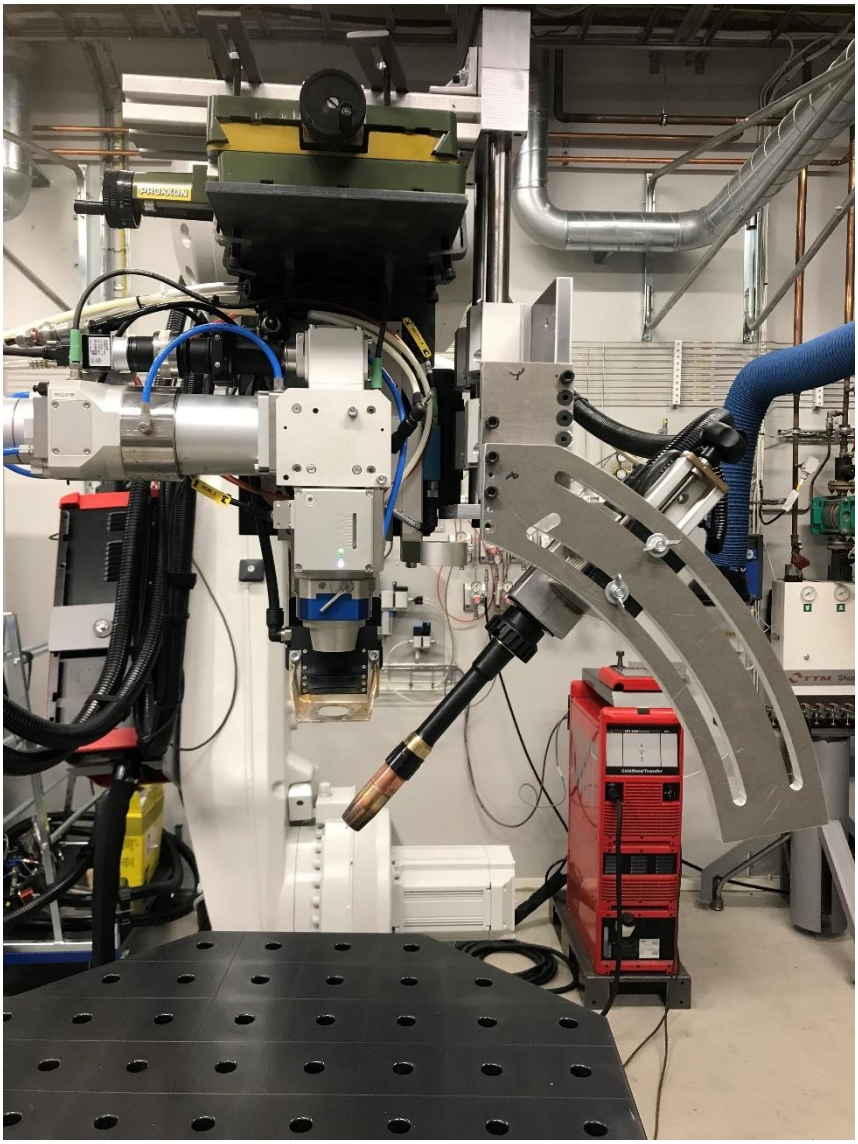


Figure 11. The laser arc hybrid welding head.

The setup of the fixture and clamping is seen in Figure 12. A welding table with two stops and five clamps are used. Four of the clamps presses the material down towards the table and the fifth one works in an angel of approximately 45° degrees which then also presses the materials together. The stops works as both counter forces and helps to align the materials.

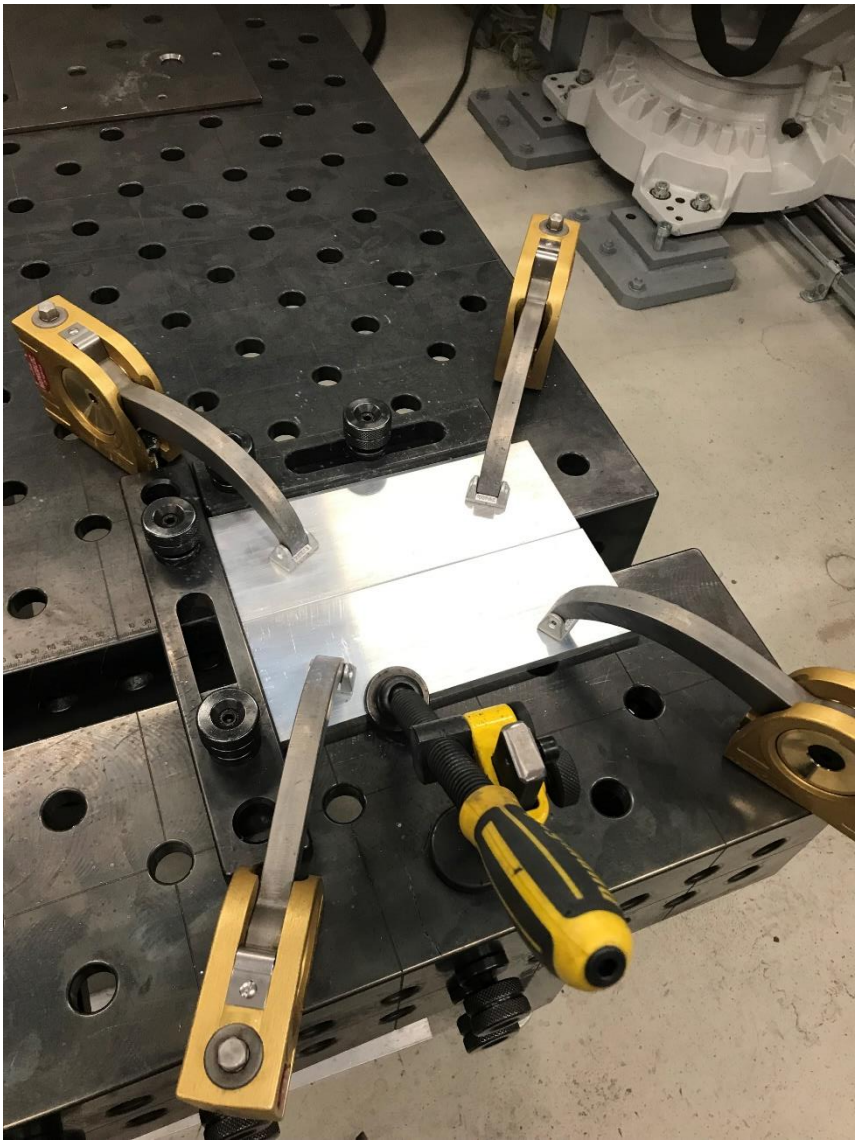


Figure 12. Clamping of the materials for welding tests.

3.5 Welding trials

Before the welding trials the materials are cleaned with 95 % ethanol and whipped of with paper towels.

The materials are fixtured and clamped as shown in Figure 12 and then before every weld trial a “dry run” is performed with a simulated laser beam. The “dry run” is performed to inspect that the laser beam and welding torch are centred, if they are not the path of the robot are adjusted. The alignment is done to keep the trials consistent.

Also, before the welding, the sickout of the MIG torch is adjusted. If it has been some time after a welding trial, for instance in the morning, shielding gas is flushed for 15s to make ensure pure shielding gas is present in the whole systems.

The length of a weld is approximately 210 mm, and a typical welded piece is shown in Figure 13.

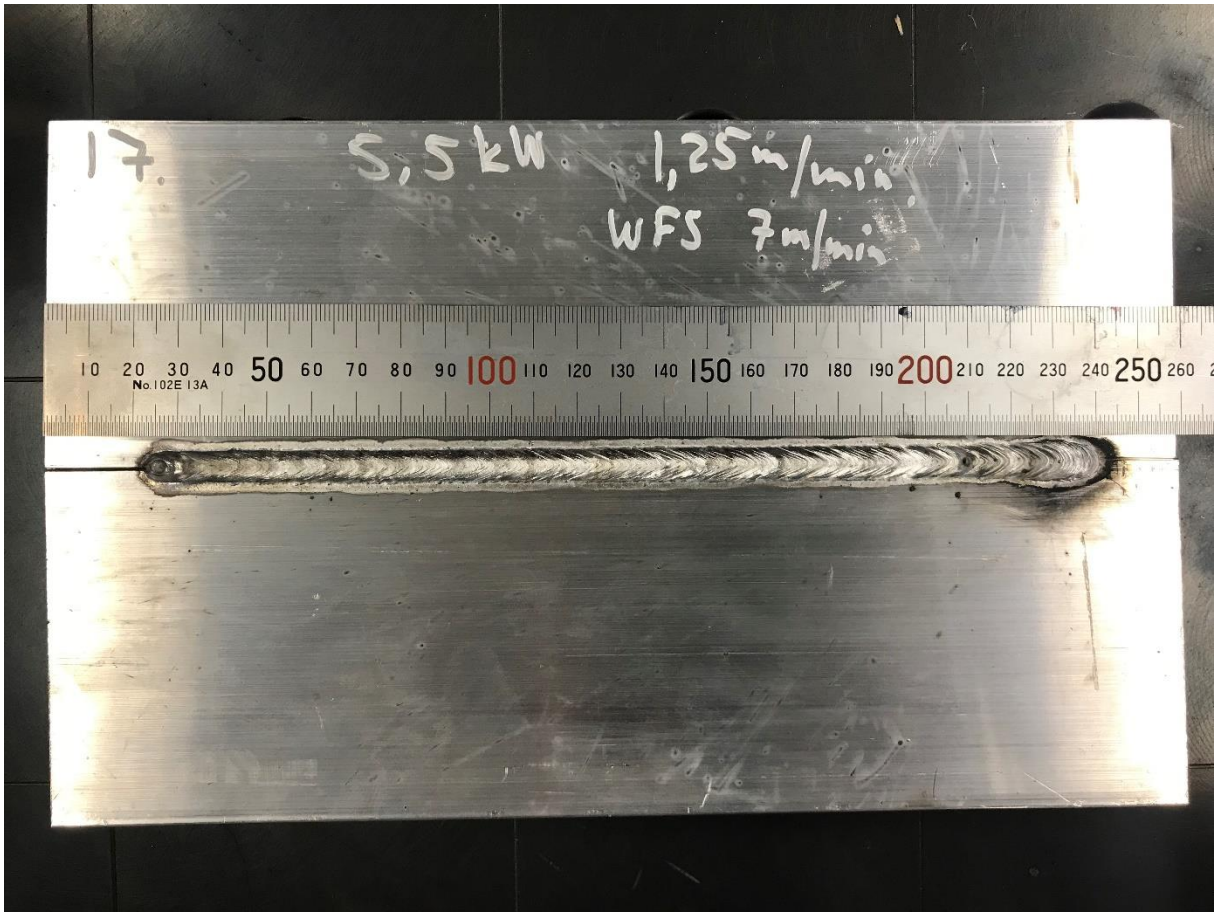


Figure 13: A test welded piece.

The welding parameters for the MIG process as well as the welding speed, laser power and laser focus are set in the program for the robot and the welding machine. Other parameters such as the heat source distance, angels of the laser and the MIG torch are adjusted on the welding head or by adjusting the robot.

The trials were performed with a set welding speed and MIG parameters, the laser power was changed to the lowest effect possible which gave an even full penetration.

Initially four welding speeds were chosen and then the laser power was optimized. The welding speeds was: 0,5m/min, 0,75m/min, 1m/min and 1,25m/min. Also, a highest possible welding speed was established by using the maximum power of the laser source (10kW). These five welding speeds and their associated laser powers were then used when other parameters were changed.

Welding trials were welded with different wire feed speeds and with two types of metal transfer modes, CMT and pulse.

3.5.1 Autogenous laser welds

A few autogenous laser welds were performed to give an indication to how the laser process itself affects the welding and therefore distinguish what might be caused by the interaction of the MIG and laser in the hybrid process. The laser welds were welded at 1,25m/min and the highest welding speed.

3.5.2 Permanent backing strips

Some welding trials were performed using permanent backing strips to try to mitigate the problem of the sagging root. 3mm thick sheets of the aluminium alloy 6082 was used as the backing material. The laser power needed to be increased due to the heat conduction of the backing material as well as the need for deeper penetration into the backing material. Welding speed of 0,5m/min was used to give a comparison to other welding trials. A highest welding speed was also established with regards to the laser power. The welds were non fully penetrations welds.

3.5.3 Non fully penetrated welding

One welding trial was performed on two pieces clamed together and welded on the high-end to give a non-fully penetrated weld. The weld can be seen in Figure 14.

Figure 14: Weld on the high-end of two pieces.

3.6 Assessment of the welds

The assessment of the welds is done by different methods. First the weld is visually inspected according to the standards mentioned earlier. To look for internal defects the welds are cross sectioned and etched. By etching the cross section of the weld, the weld profile can be distinguished.

3.6.1 Visual inspection

Welds are examined according to the standards mentioned earlier, the topside according to *Welding – Arc-welded joints in aluminium and its alloys – Quality levels for imperfections*, ISO 10042 and the root according to *Electron and laser-beam welded joints – Requirements and recommendations on quality levels for imperfections – Part 2: Aluminium, magnesium and their alloys and pure copper*, ISO 13919-2.

3.6.2 Cutting of the weld

Depending on the objective after cutting, the cutting direction was performed in two different ways. If the weld is to be etched to analyse the penetration profile, a smaller piece is cut orthogonal to the welding direction. To get an indication for porosity in the weld, a piece can be cut along with the weld, a median section of the weld. Splitting the weld in half reveals most porosity since most pores are in the middle of the weld. Examples of cut out pieces is shown in Figure 15, the picture to the left is a piece where the cut is along the weld and the right is a piece that have been etched. The pieces that are cut along the weld is approximately 40mm to 50mm wide.

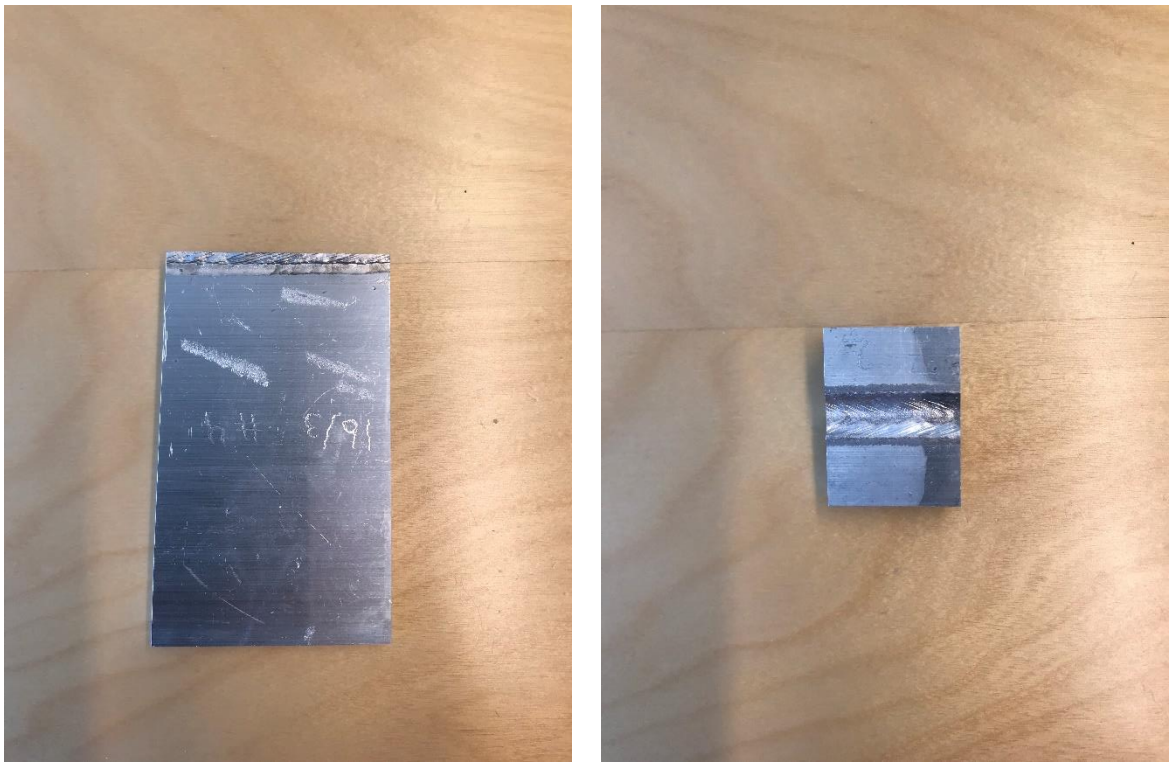


Figure 15: Different cut pieces, to the left a median cross section of the weld and to the right a cross section of the weld.

3.6.3 Sample preparation

As preparation for etching, the material is grinded and finally polished. The grinding is performed in steps and for each step the grit of the sandpaper gets finer. The cut piece is first grinded with a 600-grit sandpaper and then the following steps are used: 1200, 2500 and 4000. When grinding is completed, the piece is washed with 95% ethanol.

The polishing is done with a polishing pad, made for polishing aluminium, with a diamond paste the size of 1 micron. The time between the polishing and the etching is short to reduce the formation of aluminium oxide.

The etching is done in a sodium hydroxide. 10 grams of dry sodium hydroxide are dissolved in approximately 25-30ml of water. The pieces are held down in the mixture for around 30-45s, then the pieces get rinsed in water and then with ethanol before it is dried by a heat blower.

After the pieces are etched, a light optical microscope of the model Kappa Zelos-285C GV is used to examine and photograph the pieces. An example of a photograph of an etched part is shown in Figure 16.

When the piece is etched, the fusion line becomes easier to distinguish and the heat affected zone can be dimly seen.

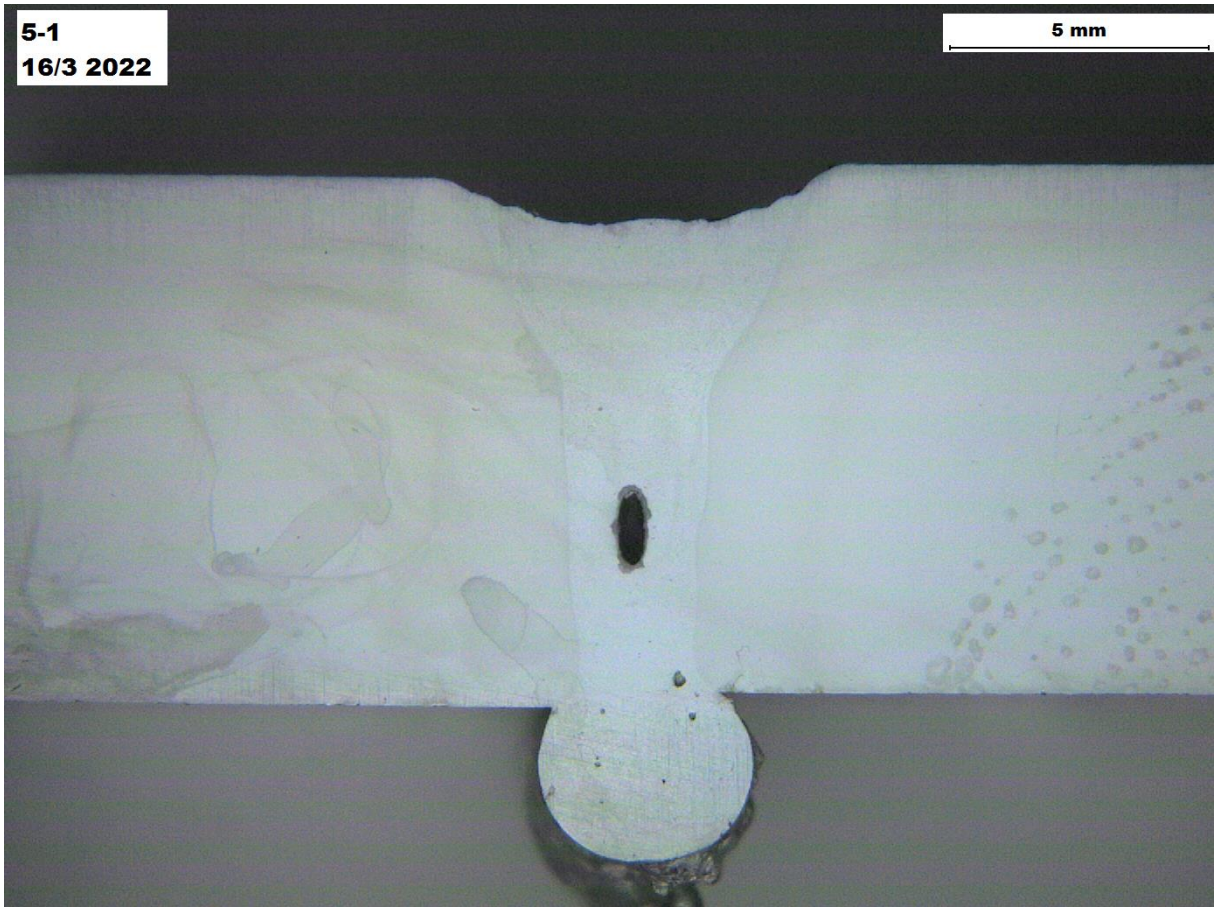


Figure 16: Image of an etched weld.

3.6.4 Hardness testing

The hardness testing was performed using the Vickers hardness test. Cut out welds are mounted in thermoplastic before grinding and etching to ease handling of the samples during testing. A mounted sample and its cross section is shown in Figure 17

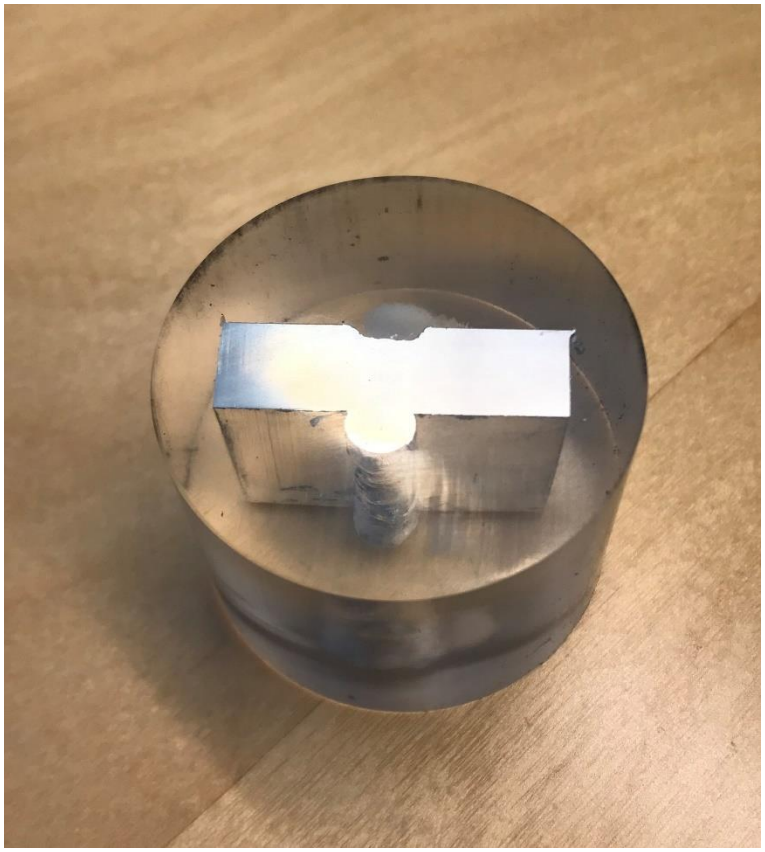


Figure 17: Cross section of weld mounted in thermoplastic.

To perform a Vickers hardness test a tool formed as a pyramid is pressed, by a known force, into the material that is to be tested. Then the diagonal of the indentation is measured. The force is applied in a controlled manner to avoid vibrations, shock or overload. From the start of applying force to the specific force is reached the time is 7^{+1}_{-5}s.

Due to the work hardening of the material when multiple indentions are made there is a minimum distance between the indentions so that they do not interfere with each other.

The testing method is described in the standard *Metallic materials – Vickers hardness test – Part 1: Test method*, SS-EN ISO 6507-1.

The entity of Vickers is pascal, the symbol is HV and how to calculate the value is seen in Eq. 3.

$$HV = 0{,}1891 * \frac{F}{d^2} \qquad \textit{Eq. 3}$$

HV is the Vickers hardness.
F is the test force in newtons (N).
d is the mean diagonal length of the indentation (mm).

The hardness test was performed as a microhardness test, HV0.1, which means that 0,1kgf is applied according to table 4 in *Metallic materials – Vickers hardness test – Part 1: Test method,* SS-EN ISO 6507-1.

The diagonals of the indentions are made by and measured in a microscope in a hardness testing machine of the model Qness Q10.

4 Result and discussion

In this section the results from the welding trials as well as observations will be presented. In the sections a table with the welding trials relevant for the section will be presented. A few of the welding parameters that was not change or just have small adjustment during the welding trials can be seen in Table 7.

A table of all the welding trials and their parameters can be seen in appendix 1.

Initial test welding results showed two defects that affects the quality of the welds, excessive penetration and large internal, irregular pores.

Further in this chapter leading laser configurations is used if nothing else is mentioned.

4.1 Setting of laser power

The welding tests with set welding speed gave indications that there is less pores when welding at 0,5m/min and the number of pores increases with the welding speed. There are more surface breaking pores at 0,75m/min than for the lower and higher welding speed. A few pictures of test welds at different welding speeds, that have been cut parallel to the welding direction are shown in Figure 18.

Most of the pores have an unregular shape and are placed in the centre of the weld. Therefore, the pores are determined to be process induced due to the information given in section Porosity2.4.7. Most distinctly this can be seen at the welding speed of 1,25 m/min. The pores are positioned at different height in the thickness direction. The welding was performed with a wire feed speed of around 6m/min. The different height of the pores indicates that the pores are trapped when the melted aluminium solidifies and therefore the slower the welding speed is the more time the pores have to “escape”.

In Table 8 the parameters of the first welding trials can be seen. The trials that had a good penetration and lowest laser power of the different welding speeds were: nr 8,18 for 0,5m/min, nr 10,20,21 for 0,75m/min, nr 4 for 1m/min and nr 15-17 for 1,25m/min.

Table 8: Welding speeds and laser power used in the welding trials.

Designation	Power [kW]	Speed[m/min]	Heat source distance [mm]	Characteristic	Wire Feed [m/min]	Voltage [V]	Current [A]	Heat input [kJ/mm]
1	7	1	3	Pulse	6	19.2	91	0.52
2	6	1	3	Pulse	6	18.7	95	0.47
3	5.5	1	3	Pulse	6	18.5	95	0.44
4	5	1	3	Pulse	6	18.8	98	0.41
5	4.5	1	3	Pulse	6	18.3	98	0.38
6	2.5	0.5	3	Pulse	6	19.9	93	0.52
7	3.5	0.5	3	Pulse	6	18.9	99	0.64
8	3.75	0.5	3	Pulse	6	18.8	97	0.67
9	4.5	0.75	3	Pulse	6	19	97	0.51
10	4.25	0.75	3	Pulse	6	18.5	99	0.49
11	4	0.75	3	Pulse	6	18.3	100	0.47
12	7	1.25	3	Pulse	6	18.7	96	0.42
13	6	1.25	3	Pulse	6	18.4	99	0.38
14	5.75	1.25	3	Pulse	6	18.4	101	0.37
15	5.5	1.25	3	Pulse	6	18.4	98	0.35
16	5.5	1.25	5	Pulse	6	17.6	104	0.35
17	5.5	1.25	5	Pulse	7	18.6	118	0.37
18	3.75	0.5	5	Pulse	6.5	18.8	107	0.69
19	3.25	0.5	5	Pulse	6	18.9	95	0.61
20	4.25	0.75	5	Pulse	7	18.7	120	0.52
21	4.25	0.75	5	Pulse	8	19.4	132	0.54

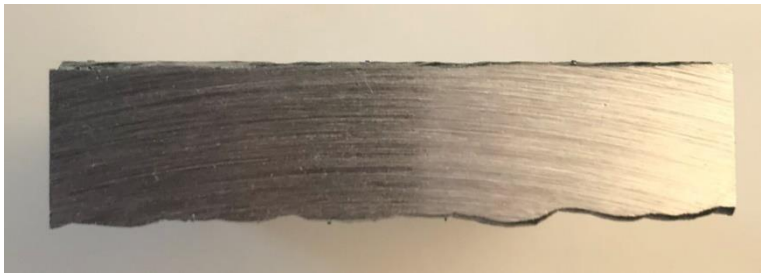
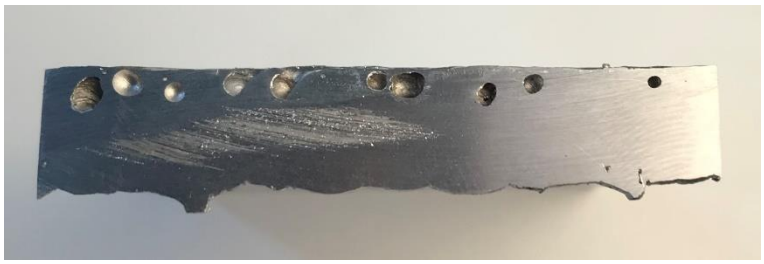
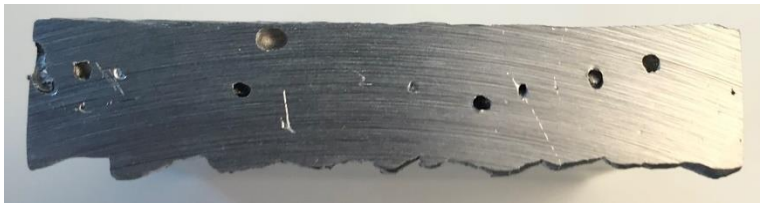
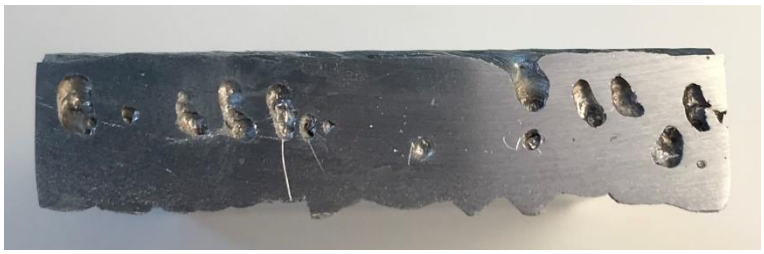
Welding speed (m/min)	Test designation	Median section of the weld
0,5	18	
0,75	21	
1,0	4	
1,25	16	

Figure 18: Median section of hybrid welds at different welding speeds.

Cross sections of the same welds as in Figure 18 are shown in Figure 19. The area of the weld gets smaller with increased welding speed and laser power.

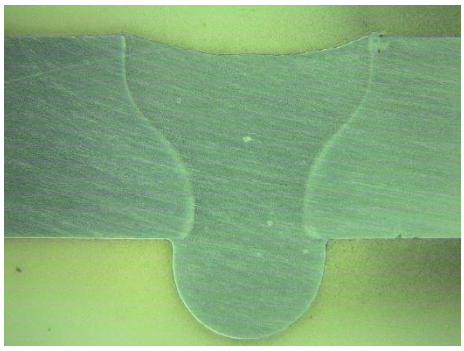
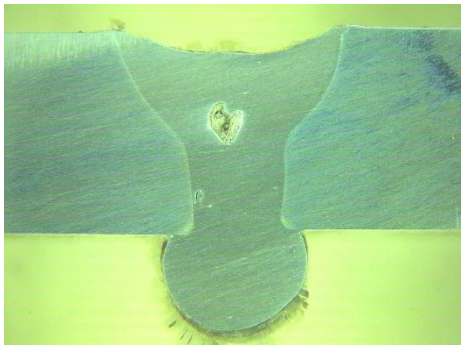
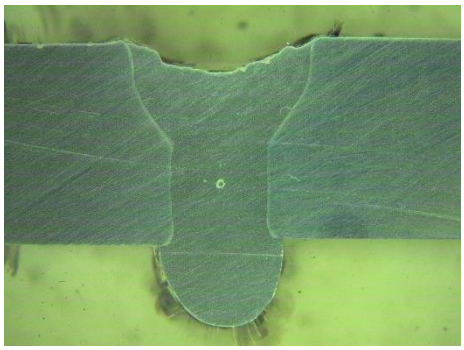
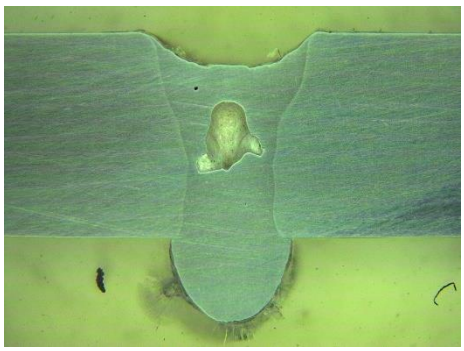
Welding speed (m/min)	**Test designation**	**Cross section of the weld**
0,5	18	
0,75	21	
1,0	4	
1,25	16	

Figure 19: Cross section of hybrid welds at different welding speeds.

4.2 Autogenous laser welds

The autogenous laser welds welded at 1,25m/min and at 4m/min are shown in Figure 20. The weld performed at the welding speed of 4m/min was the weld with the highest welding speed that gave an even penetration at maximum laser power. Table 9 shows the welding trials and parameters for the autogenous laser welds that was performed. Similar frequency and type of welding defects are seen for both the autogenous and LAHW process at welding speeds of 1,25m/min. In Figure 21 a cross section is shown from both hybrid and laser welding. The results indicates that it is not primarily the interaction between the MIG and the laser in the hybrid process that contributes to the pores due to the fact it looks similar in the autogenous welded welds at the same welding speed.

At the welding speed of 4m/min and power of 10kW the weld does only show one pore that can be considered as a larger unregular pore.

Table 9: Autogenous laser welding trials and their parameters.

Designation	**Power [kW]**	**Speed[m/min]**	**Characteristic**	**Heat input [kJ/mm]**
22	3.5	0.5	Autogen	0.42
23	4	0.5	Autogen	0.48
24	5	0.5	Autogen	0.60
25	7	1.25	Autogen	0.34
26	8	1.25	Autogen	0.38
27	5.75	1.25	Autogen	0.28
28	5	1.25	Autogen	0.24
29	5.3	1.25	Autogen	0.25
30	10	4	Autogen	0.15

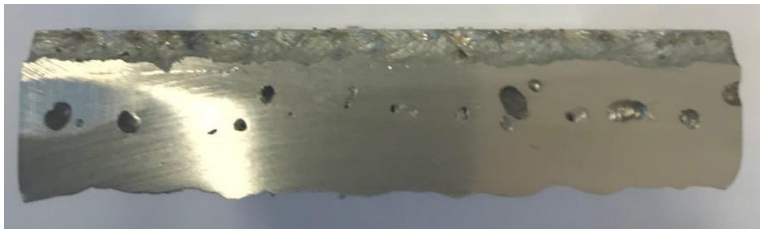
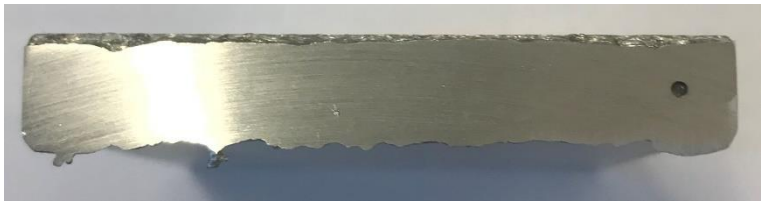
Welding speed (m/min)	Laser power (kW)	Median section of laser welded welds
1,25	5,3	
4	10	

Figure 20: Median section of autogenous laser welded welds at different welding speed.

Figure 21 shows a cross section from both hybrid and autogenous laser welding. Both cross sections show a similar pore. The root and the width of the hybrid weld is larger than the autogenous laser weld.

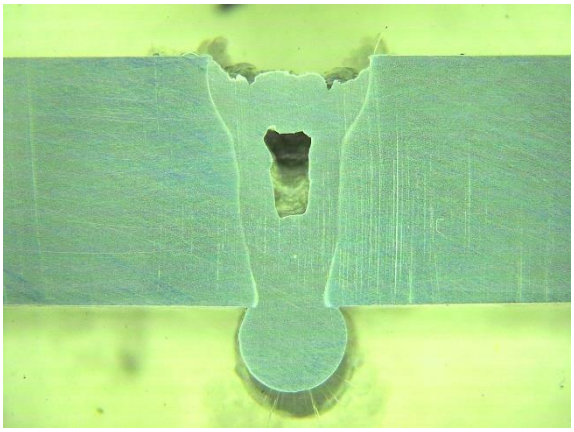
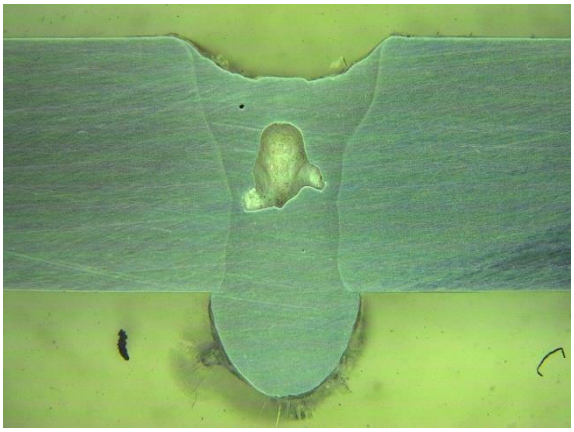
Autogenous laser	Laser arc hybrid
	

Figure 21: Cross section of a laser weld, picture to the left, and a hybrid weld, picture to the right, at 1,25m/min welding speed.

4.3 CMT as metal transfer mode

Median sections of the hybrid welds performed with CMT as transfer mode is shown in Figure 22. Welding speed and power of the laser is the same as for the welding trials shown in

Figure 18. A lot of pores can be seen, and all the welds have surface breaking pores. Example of weld with surface breaking pores is seen in Figure 23. The same tendency can be seen regarding at which height the pores are located. The higher the welding speed is, the deeper the concentration of pores in the weld are. In Table 10 the welding trials and their parameters are shown.

Table 10: Welding parameters for the CMT welded welds.

Designation	**Power [kW]**	**Speed [m/min]**	**Heat source distance [mm]**	**Characteristic**	**Wire Feed [m/min]**	**Voltage [V]**	**Current [A]**	**Heat input [kJ/mm]**
39	4.25	0.75	5	CMT	6	11.6	147	0.48
40	4.25	0.75	5	CMT	5	10.6	97	0.42
41	5	1	5	CMT	5	10.4	98	0.36
42	5.5	1.25	5	CMT	6	11.2	146	0.34
43	3.75	0.5	5	CMT	5	11	96	0.58

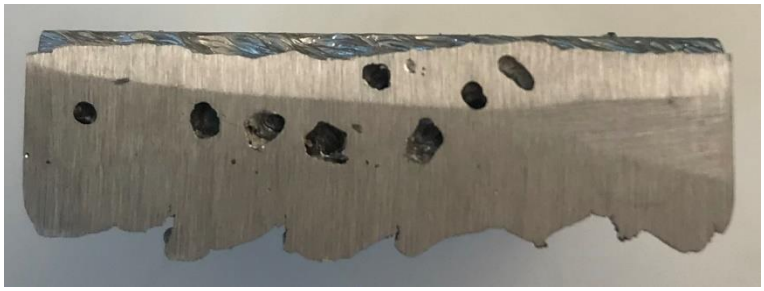
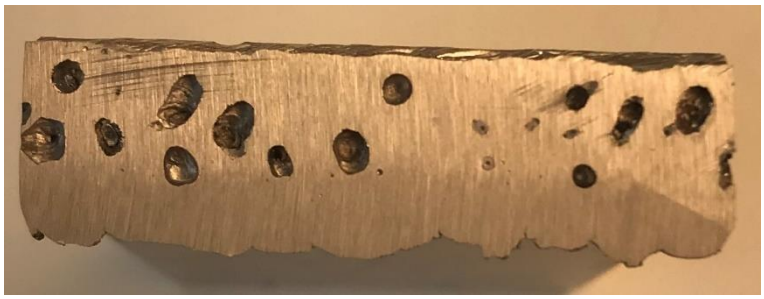
Welding speed (m/min)	Test designation	Median section of the weld
0,5	43	
0,75	40	
1,0	41	
1,25	42	

Figure 22: Median section of hybrid welds with CMT as metal transfer mode.

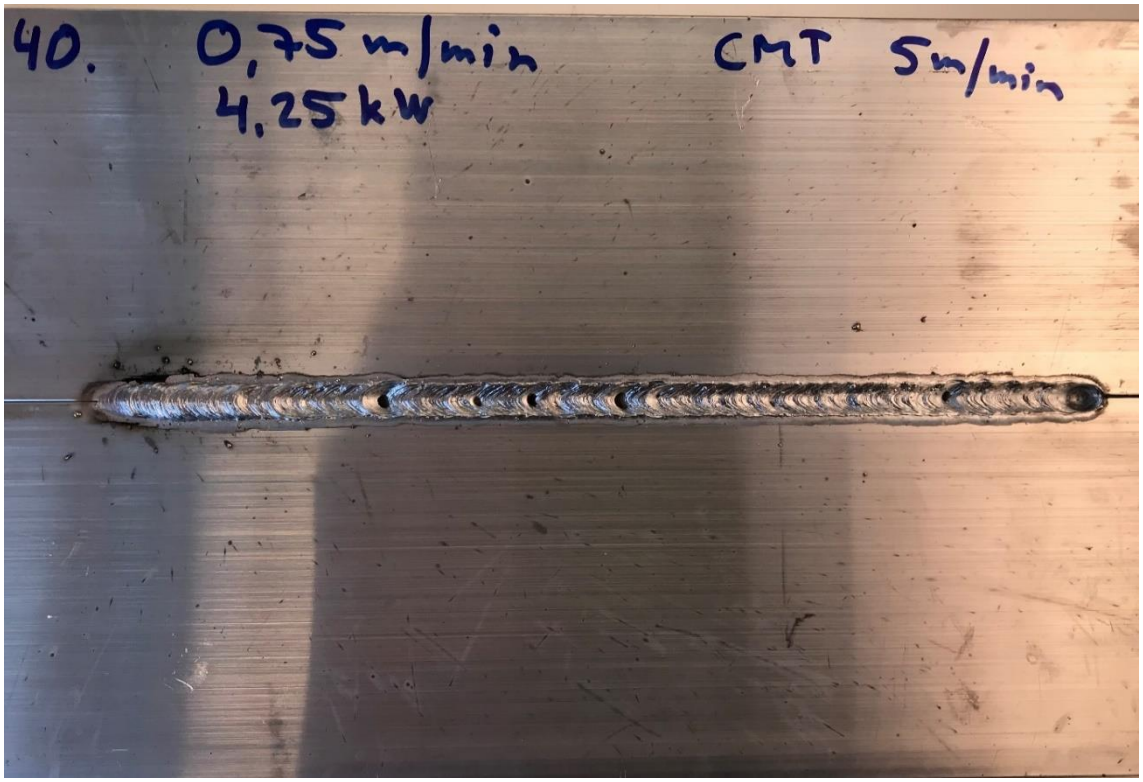


Figure 23: Top of weld welded with a welding speed of 0,75m/min and CMT as metal transfer mode.

There are probably two reasons for the higher number of pores when using CMT compared to a pulsed synergy. The CMT welding is “colder” with less heat input and therefore the solidification of the weld is faster. Another possibility is that the CMT short circuit drop transferee might affect the weld pool more and by that increase the keyhole instability.

The argument regarding the lower heat input by CMT giving more pores is since there is a lot more pores at the welding speed of 0,5 m/min in contrast to the weld performed with pulse mode.

When the metal transfer mode is changed other welding parameters might have to be changes as well to optimise the welding process. CMT might for instance require a different heat source distance than pulse welding. Therefore, it is not fair to make any complete conclusion regarding the difference between the two metal transfers.

4.4 Arc leading and laser leading

When the directions of welding were changed, from laser leading to arc leading, a big difference in visual appearance was observed. During arc leading welding there is a lot of soot generation on the surface. A comparison is shown in Figure 24. Another difference in appearance is that the leading arc welds does not have the same uniformity as the welds performed with leading laser. The size of the root is unchanged when going from arc leading

to laser leading with the same parameters. The parameters of the arc leading trials are seen in Table 11.

Table 11: Welding parameters for the arc leading welding trials.

Designation	**Weld configuration**	**Power [kW]**	**Speed[m/min]**	**Heat source distance [mm]**	**Characteristic**	**Wire Feed [m/min]**	**Voltage [V]**	**Current [A]**	**Heat input [kJ/mm]**
46	leading arc	4.25	0.75	5	Pulse	6	23	107	0.54
47	leading arc	10	4	5	Pulse	10	27.3	175	0.22

Both welds in Figure 24 and Figure 25 are welded at 4m/min welding speed and 10kW of laser power.

In Figure 25 cross sections from the different configurations can be seen. The weld is narrower for the leading arc than for the leading laser.

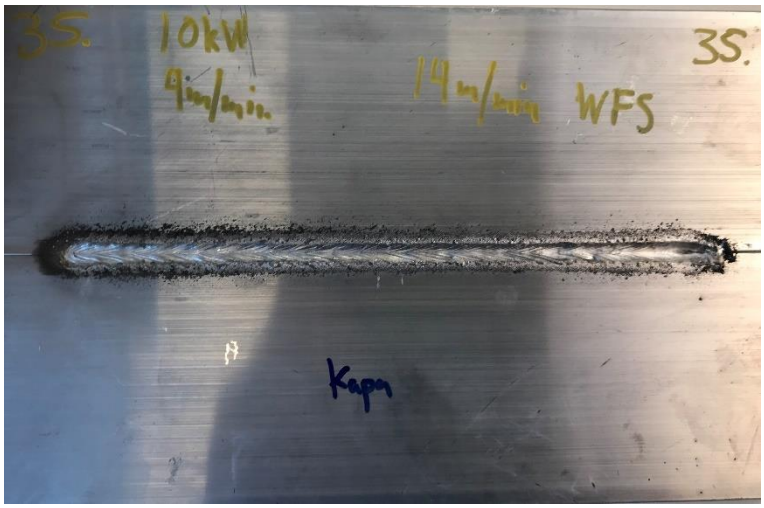
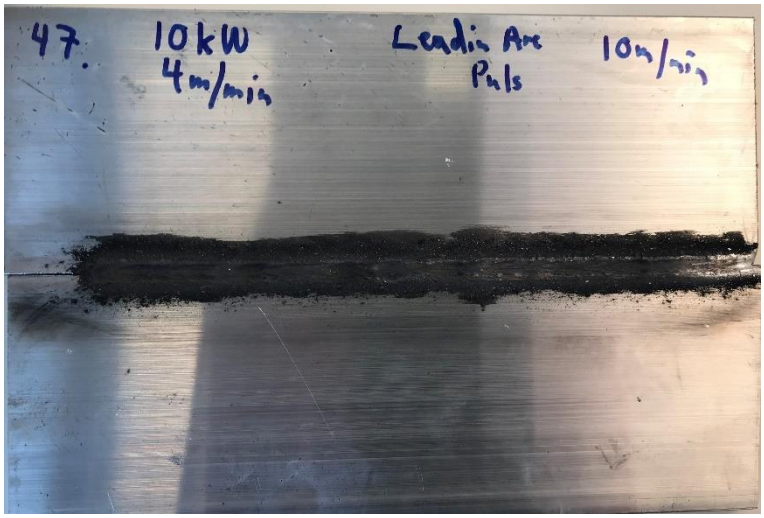
Laser leading	
Arc leading	

Figure 24: Difference in appearances of laser leading and arc leading welds.

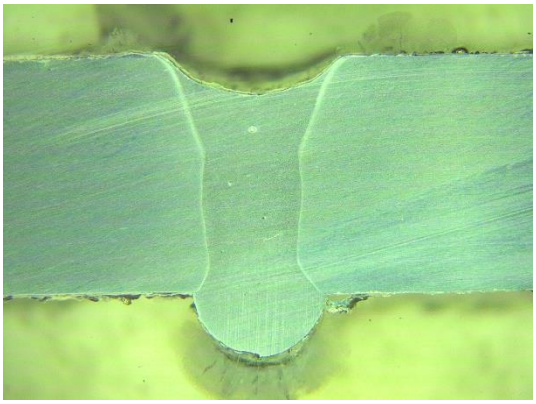
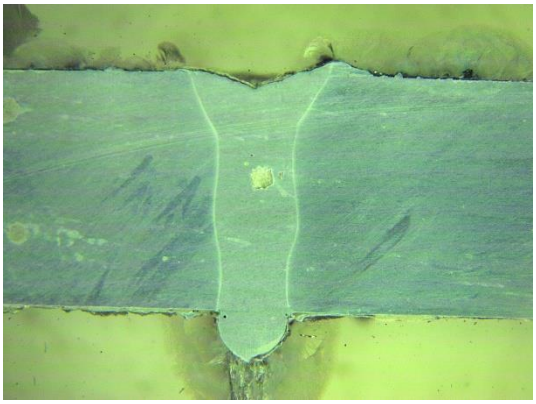
Laser leading	**Arc leading**
	

Figure 25: Cross sections of welds welded with laser- and arc leading.

4.5 Increased wire feed speed

Median sections of welds with increased wire feed speed using pulse mode are shown in Figure 26. The increasing of wire feed speed results in more power from the MIG process. The wire feed speed used for the welds in Figure 26 was 10m/min. In comparison to the median sections in Figure 18 and Figure 22 there is less pores when the MIG process power is higher. The welding parameters used for the welding trials can be seen in Table 12.

Table 12: Welding parameters for the welding trials with increased wire feed speed.

Designation	**Power [kW]**	**Speed[m/min]**	**Heat source distance [mm]**	**Characteristic**	**Wire Feed [m/min]**	**Voltage [V]**	**Current [A]**	**Heat input [kJ/mm]**
31	4.25	0.75	5	Pulse	10	27	184	0.74
32	5	1	5	Pulse	10	27	184	0.60
33	5.5	1.25	5	Pulse	10	26.8	184	0.50
38	4	0.75	5	Pulse	10	26.8	187	0.72

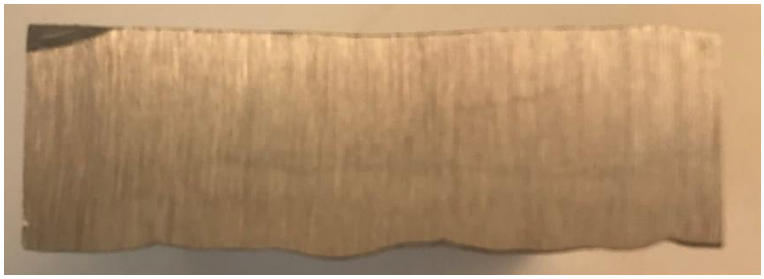
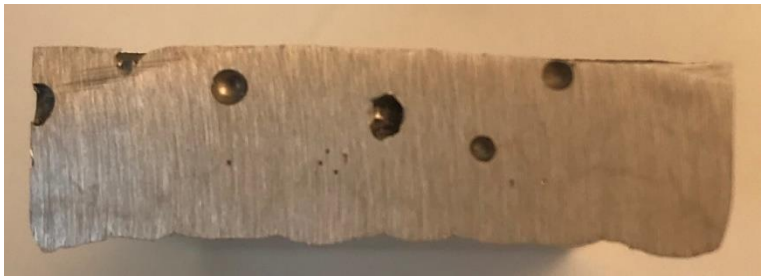
Welding speed (m/min)	Test designation	Median section of the weld
0,75	31	
1,0	32	
1,25	33	

Figure 26: Median section of hybrid welds with pulse mode and wire feed speed of 10m/min

Figure 27 shows three different cross sections welded with the same welding speed and laser power but with different settings for the MIG process. Due to the increased power from the MIG process, the weld with higher wire feed speed is wider.

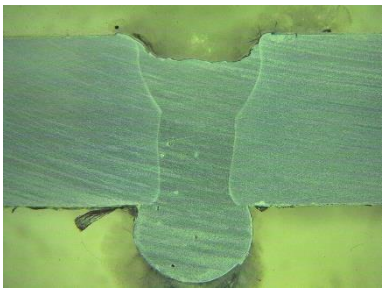
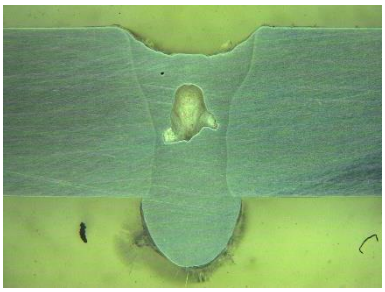
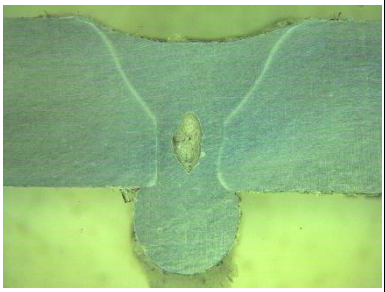
CMT, 6m/min	Pulse, 6m/min	Pulse, 10m/min
		

Figure 27: Cross sections welded with 1,25m/min welding speed, laser power of 5,5kW and different parameters and settings on the MIG process.

With increased wire feed speed the heat input increases and the less pores are created. Alternatively, more pores escape the melt pool before it solidifies. This is the reason the number of pores is less than for the welds with lower wire feed speed.

4.6 Higher welding speed

A cross- and median section of a weld welded at the highest welding speed is seen in Figure 28. The wire feed speed was 14m/min and pulse transfer mode were used. The top and the bottom of the weld can be seen in Figure 29. The root has some uneven penetration in a few places, mostly in the beginning of the weld.

The welding parameters can be seen in Table 13.

Table 13: Welding parameters for the trials using higher welding speed.

Designation	**Power [kW]**	**Speed[m/min]**	**Heat source distance [mm]**	**Characteristic**	**Wire Feed [m/min]**	**Voltage [V]**	**Current [A]**	**Heat input [kJ/mm]**
34	10	4	5	Pulse	10	26.5	183	0.22
35	10	4	5	Pulse	14	29.9	231	0.25
36	10	4	5	Pulse	16	32.1	260	0.28
37	10	3.8	5	Pulse	16	31.6	267	0.29

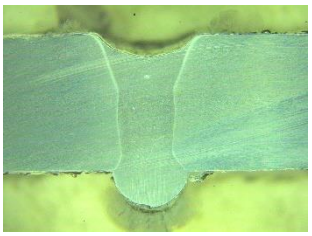
Welding speed (m/min)	Cross section	Median section
4		

Figure 28: Cross- and median section of the weld welded with the highest welding speed.

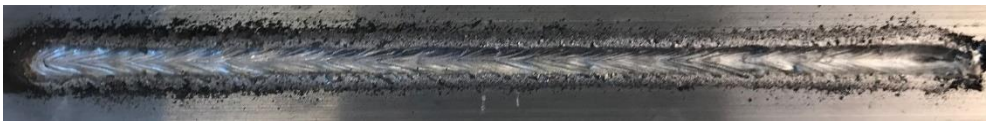
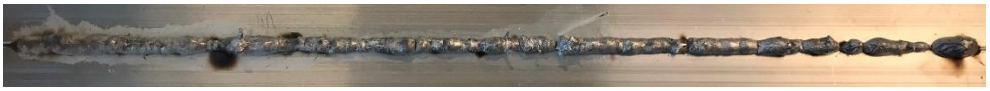
Topside	
Backside	

Figure 29: Top- and backside of the weld with highest welding speed.

A comparison between the autogenous laser weld and the laser arc hybrid weld is seen in Figure 30 and Figure 31. The hybrid weld is wider at the top and has a larger root. The type and amount of porosity are similar.

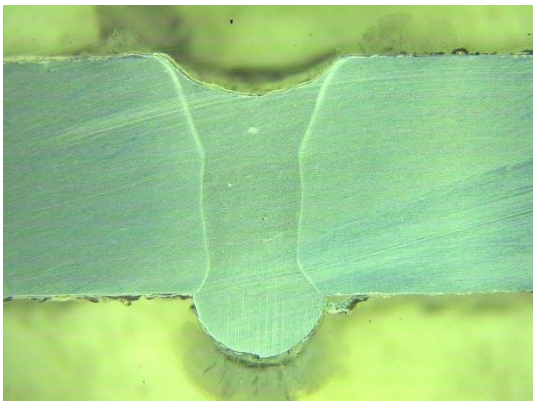
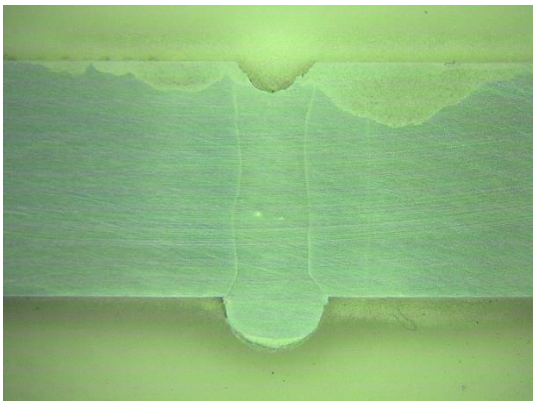
Laser arc hybrid weld	Autogenous laser weld
	

Figure 30:Cross section of welds welded at 4m/min welding speed.

Laser arc hybrid weld	Autogenous laser weld
	

Figure 31:Median section of welds welded at 4m/min welding speed.

The laser welding process gets more stable at higher welding speeds. There is less process induced porosity at higher welding speeds which indicates that higher welding speed increases the keyhole stability. This is consistent with previously mentioned literature in section 2.4.5 Welding speed.

4.7 Backing material

Cross- and median section of welds welded with 3mm permanent backing strips is seen in Figure 32. As seen in the median sections, porosity was found around the edge between the base material and the backing material.

Welding parameters for the welding trials using backing material is seen in Table 14.

Table 14: Welding parameters for the trials using backing material.

Designation	Thickness	Power [kW]	Speed[m/min]	Heat source distance [mm]	Characteristic	Wire Feed [m/min]	Voltage [V]	Current [A]	Heat input [kJ/mm]
48	8+3	4	0.5	5	Pulse	6	23.4	107	0.78
49	8+3	4.75	0.5	5	Pulse	6	23.6	107	0.87
50	8+3	10	3	5	Pulse	10	29.8	244	0.35
51	8+3	10	3.9	5	Pulse	14	28.6	256	0.27
52	8+3	10	4.2	5	Pulse	14	29.7	246	0.25
53	8+3	10	4.2	5	Pulse	14	29.1	251	0.25
54	8+3	10	4.2	5	Pulse	14	29	250	0.25

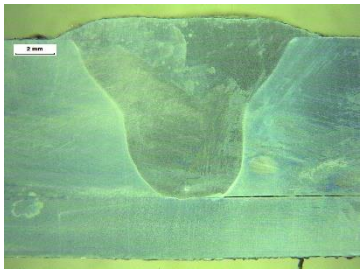
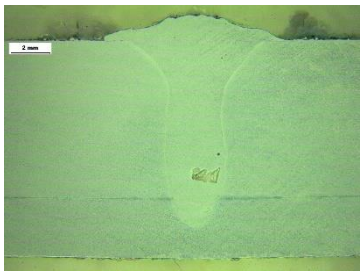
Welding speed (m/min)	Cross section	Median section
0,5		
3		

Figure 32: Cross- and median section of welds welded with permanent backing strip.

Due to the possibility that the pores are created because of the oxide layer of the backing material, a welding trial was performed with the backing and base material brushed with a stainless-steel brush to remove the oxide layer. The result showed no difference between the one with removed oxide layer and the ones in Figure 32. The median section of the weld with the oxide removed is shown in Figure 33.

Figure 33: Median section of weld where the oxide layer was removed before welding.

The keyhole of the laser seems to get unstable when the welding is not performed with full penetration.

To reduce the risk of that the backing material was contaminated, even though a test weld was performed with removed oxide layer, a weld was performed on the high end of two pieces. The result was the same as for the welding with backing material. A median section of the high-end weld, the setup seen in Figure 14, is seen in Figure 34. The penetrations of the weld

were approximately 8,5mm, the welding speed was 4,2m/min, wire feed speed was 14m/min, and the laser power was 10kW.

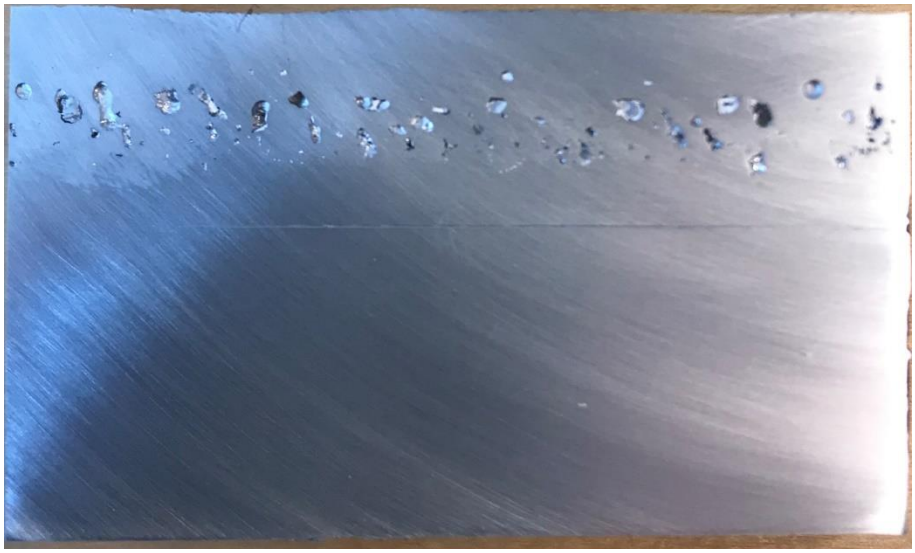


Figure 34: Median section of the high-end weld.

4.8 Results from the hardness testing of cross sections.

Figure 35 shows a hardness measurement over a cross section of a weld that been welded with 4m/min welding speed, 10kW laser power and a heat input of 0,25kJ/mm. It is the test number 35 from Table 13 The base material is harder and has a colour of red and yellow, the blue part is the softest and most of the blue is placed in the heat affected zone. As expected, a softening occurs in the heat affected zone.

The hardness of aluminium alloy 6082-t6 is approximately 100HV. [53]

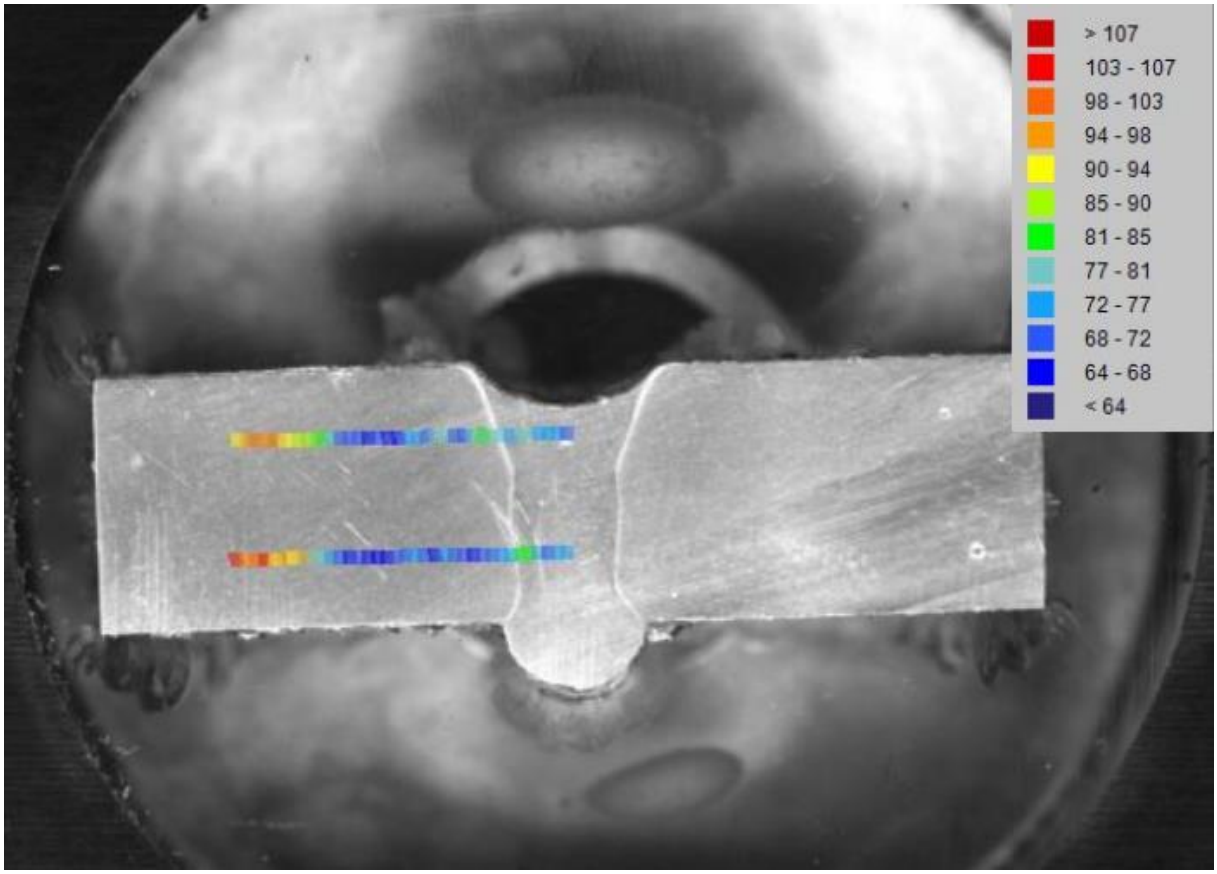


Figure 35: Hardness distribution across a cross section of a weld, testing performed according to Vickers HV0.1.

Figure 36: Hardness distribution of test nr 18 shows the hardness distribution of test number 18. The heat affected zone is larger on test sample nr 18 than on nr 35, due to the higher heat input when nr 18 was welded. A better comparison can be seen in Figure 37, which shows a diagram of the hardness over a few cross sections. To the left in the diagram is the hardness approximately in the centre of the weld and then the measurement goes out of the weld, just as the colour line in Figure 36 . The distance between the points is 0,4mm which makes the total length measured 14,4mm.

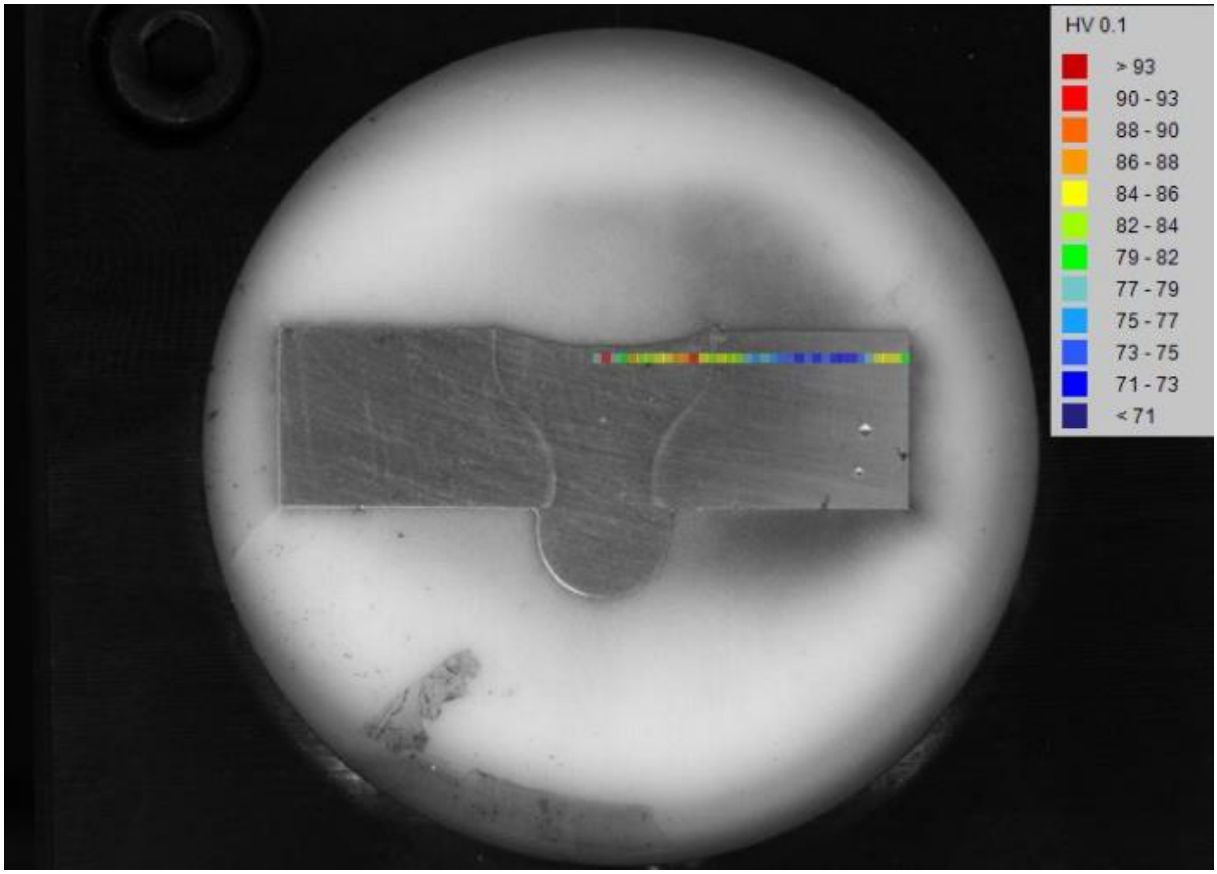


Figure 36: Hardness distribution of test nr 18

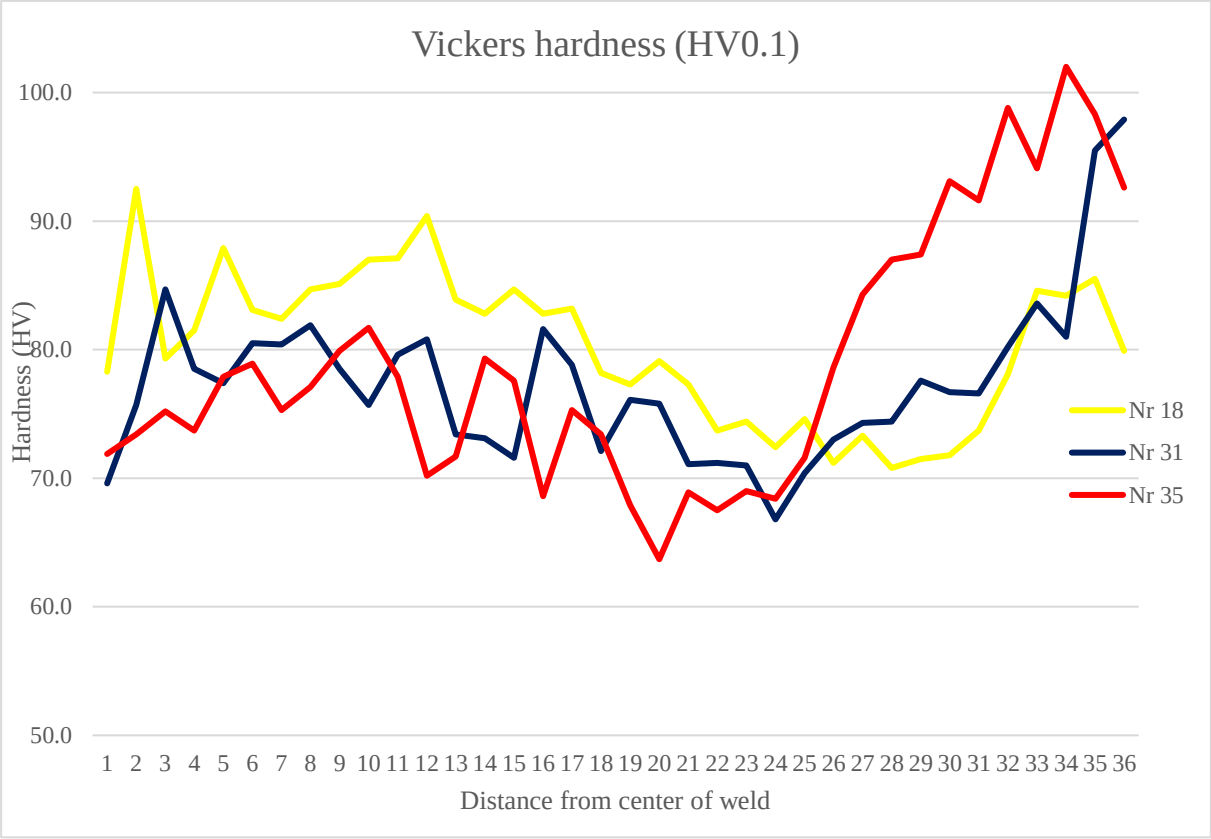


Figure 37: Diagram of the hardness across cross sections. Hardness test done according to Vickers HV0.1.

The heat input of the samples is seen in Table 15: Heat input of the hardness tested welds.. The values vary a lot, but trends of the lines can be seen. Nr 35 reaches the hardness of the base material first, which is expected due to the lowest heat input. The heat affected zone is smaller when having lower heat input.

The length of the measurements is too narrow because the hardness should stabilize when entering the non-heat affected base material.

A smaller heat affected zone means that less of the base material have lost its strength, which is beneficial to the mechanical properties.

Table 15: Heat input of the hardness tested welds.

Designation	**Heat input (kJ/mm)**
18	0,69
31	0,74
35	0,25

4.9 Assessment according to standards

Two main issues can be observed visually on all the welds with full penetration, excessive penetration, sagging of the top and incompletely filled grove. Excessive penetration is when the root it too big and sagging of the top is when the top of the weld has sagged and the top of the weld under the top of the base material. Incompletely filled grove and sagging of the top are discontinuity that looks the same, but the cause is different. Incompletely filled groove occurs because of lack of filler material and sagging of the top is when the weld is sagging because of its weight. During the welding trials no improvement of the sunken weld was seen when increasing the wire feed speed, which increases the filler material, and therefore the discontinuity is seen as sagging of the top.

The maximum allowed excessive penetration for the thickness of 8mm, and quality level C is 4mm according to *Welding – Arc-welded joints in aluminium and its alloys – Quality levels for imperfections*, ISO 10042 and 2,8mm according to *Electron and laser-beam welded joints – Requirements and recommendations on quality levels for imperfections – Part 2: Aluminium, magnesium and their alloys and pure copper*, ISO 13919-2

The maximum allowed sagging of the top for the thickness of 8mm, and quality level C is 1mm according to ISO 10042 and 1,6mm according to ISO 13919-2.

If using ISO 10042 to assess the topside the maximum allowed sagging is 1,6mm and if using ISO 13919-2 to assess the root the maximum excessive penetration allowed is 2,8mm.

In Table 16 the excessive penetration and the sagging of the top are measured in the cross sections of different welds. The biggest issue when comparing the welds to the standards is the excessive penetration and Table 16 shows a good representation of that, with only one weld within the quality levels of the imperfections.

Table 16: Excessive penetration and sagging of the top of different welds.

Welding speed, laser power and wire feed speed.	**Excessive penetration (mm)**	**Sagging of the top (mm)**
0,5m/min, 3,75kW, 6,5m/min	3,98	0,79
0,5m/min, 3,75kW, 5m/min (CMT)	3,71	0,60
1,25m/min, 5,5kW, 10m/min	4,03	1,11
4m/min, 10kW, 14m/min	2,18	1,34

Although that a weld is within limits of the standards it does not mean that other requirements are full filled e.g., aesthetic requirements. The excessive penetration and the sagging of the top would most likely be a problem if is visual appearance is part of the quality criteria as an example.

The amount of porosity cannot fully be assessed toward any standard due to the method used to compare porosity. To get a more accurate estimate of the porosity the welds must be x-rayed, and it is not applicable to use the median sections of the welds to try to do an accurate estimation of the amount of porosity. The median sections do only show the porosity that lays in the cut that been made.

No cracks were found on any of the welds.

5 Conclusions

The welding trials has been performed on 8mm thick 6082. The conclusions of the welding trials, the literature review and the results can be summarized as:

- It is possible to get laser arc hybrid welds with low amount of porosity and that satisfies the requirements of different standards relevant for quality of welding of aluminium alloys.
- Low porosity buttwelds can be achieved with welding speed of around 0,5m/min and 4m/min.
- At welding speed below ~4m/min, keyhole instability occurs which creates porosity.
- With a welding speed of ~0,5m/min the pores, created by keyhole instability, can escape before the weld solidifies. In welds welded between 0,5m/min and around 4m/min pores have less time to evaporate and there is a greater risk for porosity. At around 4m/min and above the porosity is reduced.
- Higher wire feed can increase the lower welding speed, from 0,5m/min to 0,75m/min, with keeping a low amount of porosity. With higher heat input the solidification rate of the melt is reduced and therefore pores have a longer time to “escape” the molten weld pool.
- Non fully penetrating buttwelds received higher amount of porosity than full penetration buttwelds.
- Higher welding speeds results in a possibility to reduce heat input which gives a narrower heat affected zone.
- More work can be done on weld geometry optimisation for the weldments. The work reported here had the mission to identify suitable process set-ups and data regions

6 Suggested continued work

Only one parameter has been changed at a time during the welding trials and therefore far from all types of welding configurations have been tested and evaluated. More investigation is necessary to optimize the parameters of the welding process. More testing of the heat source distance and the different angels, laser and MIG welding gun, is relevant.

A few interesting parameters to explore further is among other things the laser focus and different types of laser optics. By either changing at which height the focus point is or by changing the characteristics of the optics might have a large effect on the welding. Different size of the laser spot size might influence the keyhole stability, but only one size was used for the welding trials.

It would be of interest if higher laser power were available to investigate how the results and conclusions is applicable on thicker material.

To get a more accurate examination of the porosity, x-ray of the welds is recommended. As mentioned earlier, there is no relevant standard containing quality limits for laser arc hybrid welding of aluminium, but it is still of importance to know the amount of porosity in the weld.

A few things can be done to better understand the behaviour and stability of the keyhole. One suggestion is to record the welding process by using a high-speed camera. Another way to get a better understanding would be to model and perform a welding simulation of the process and the material.

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Appendix 1

Designation	Weld configuratic	Thickness	Power [kW	Speed[m/mi	Heat source distance [mm]	Characterist	Wire Feed [m/mi	Voltage [V]	Current [A]	Heat input [kJ/mm]
1	leading laser	8	7	1	3	Pulse	6	19.2	91	0.52
2	leading laser	8	6	1	3	Pulse	6	18.7	95	0.47
3	leading laser	8	5.5	1	3	Pulse	6	18.5	95	0.44
4	leading laser	8	5	1	3	Pulse	6	18.8	98	0.41
5	leading laser	8	4.5	1	3	Pulse	6	18.3	98	0.38
6	leading laser	8	2.5	0.5	3	Pulse	6	19.9	93	0.52
7	leading laser	8	3.5	0.5	3	Pulse	6	18.9	99	0.64
8	leading laser	8	3.75	0.5	3	Pulse	6	18.8	97	0.67
9	leading laser	8	4.5	0.75	3	Pulse	6	19	97	0.51
10	leading laser	8	4.25	0.75	3	Pulse	6	18.5	99	0.49
11	leading laser	8	4	0.75	3	Pulse	6	18.3	100	0.47
12	leading laser	8	7	1.25	3	Pulse	6	18.7	96	0.42
13	leading laser	8	6	1.25	3	Pulse	6	18.4	99	0.38
14	leading laser	8	5.75	1.25	3	Pulse	6	18.4	101	0.37
15	leading laser	8	5.5	1.25	3	Pulse	6	18.4	98	0.35
16	leading laser	8	5.5	1.25	5	Pulse	6	17.6	104	0.35
17	leading laser	8	5.5	1.25	5	Pulse	7	18.6	118	0.37
18	leading laser	8	3.75	0.5	5	Pulse	6.5	18.8	107	0.69
19	leading laser	8	3.25	0.5	5	Pulse	6	18.9	95	0.61
20	leading laser	8	4.25	0.75	5	Pulse	7	18.7	120	0.52
21	leading laser	8	4.25	0.75	5	Pulse	8	19.4	132	0.54
22	laser	8	3.5	0.5	-	Autogen	-			0.42
23	laser	8	4	0.5	-	Autogen	-			0.48
24	laser	8	5	0.5	-	Autogen	-			0.60
25	laser	8	7	1.25	-	Autogen	-			0.34
26	laser	8	8	1.25	-	Autogen	-			0.38
27	laser	8	5.75	1.25	-	Autogen	-			0.28
28	laser	8	5	1.25	-	Autogen	-			0.24
29	laser	8	5.3	1.25	-	Autogen	-			0.25
30	laser	8	10	4	-	Autogen	-			0.15
31	leading laser	8	4.25	0.75	5	Pulse	10	27	184	0.74
32	leading laser	8	5	1	5	Pulse	10	27	184	0.60
33	leading laser	8	5.5	1.25	5	Pulse	10	26.8	184	0.50
34	leading laser	8	10	4	5	Pulse	10	26.5	183	0.22
35	leading laser	8	10	4	5	Pulse	14	29.9	231	0.25
36	leading laser	8	10	4	5	Pulse	16	32.1	260	0.28
37	leading laser	8	10	3.8	5	Pulse	16	31.6	267	0.29
38	leading laser	8	4	0.75	5	Pulse	10	26.8	187	0.72
39	leading laser	8	4.25	0.75	5	CMT	6	11.6	147	0.48
40	leading laser	8	4.25	0.75	5	CMT	5	10.6	97	0.42
41	leading laser	8	5	1	5	CMT	5	10.4	98	0.36
42	leading laser	8	5.5	1.25	5	CMT	6	11.2	146	0.34
43	leading laser	8	3.75	0.5	5	CMT	5	11	96	0.58
44	leading laser	8	3.75	0.5	5	PMC	6	23.7	107	0.75
45	leading laser	8	3.75	0.5	5	PMC	4	23.7	61	0.62
46	leading arc	8	4.25	0.75	5	Pulse	6	23	107	0.54
47	leading arc	8	10	4	5	Pulse	10	27.3	175	0.22
48	leading laser	8+3	4	0.5	5	Pulse	6	23.4	107	0.78
49	leading laser	8+3	4.75	0.5	5	Pulse	6	23.6	107	0.87
50	leading laser	8+3	10	3	5	Pulse	10	29.8	244	0.35
51	leading laser	8+3	10	3.9	5	Pulse	14	28.6	256	0.27
52	leading laser	8+3	10	4.2	5	Pulse	14	29.7	246	0.25
53	leading laser	8+3	10	4.2	5	Pulse	14	29.1	251	0.25
54	leading laser	8+3	10	4.2	5	Pulse	14	29	250	0.25

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