FACULDADE DE TECNOLOGIA SENAI CIMATEC
PÓS - GRADUAÇÃO EM CONFORMAÇÃO E UNIÃO DE MATERIAIS

DANILO LEITE RIBEIRO

GAP BRIDGING ABILITY IN ALUMINUM LASER WELDING

Salvador
2016

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Trabalho de Conclusão do Curso apresentado ao curso de Pós-Graduação em Conformação e União de Materiais da Faculdade de Tecnologia SENAI CIMATEC como requisito final para a obtenção do título de Especialista.

Orientador: Wilberth Harold Deza Luna
Co-Orientador: Charles Chemale Yurgel

Salvador

Ficha catalográfica elaborada pela Biblioteca da Faculdade de Tecnologia SENAI CIMATEC

R484g Ribeiro, Danilo Leite

Gap bridging ability in aluminum laser welding / Danilo Leite Ribeiro. – Salvador, 2016.

56 f. : il. color.

Orientador: Prof. Dr. Wilberth Harold Deza Luna.
Coorientador: Prof. Dr. Charles Chemale Yurgel.

Monografia (Especialização em Conformação e União de Materiais) – Programa de Pós-Graduação, Faculdade de Tecnologia SENAI CIMATEC, Salvador, 2016.
Inclui referências.

1. Solda por espaçamento. 2. Alumínio - Soldagem. 3. Solda a laser. I. Faculdade de Tecnologia SENAI CIMATEC. II. Luna, Wilberth Harold Deza. III. Yurgel, Charles Chemale. IV. Título.

CDD: 620.11

NDI - 02

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Aprovado em 19 de Setembro de 2016.

Banca Examinadora

____
Wilberth Harold Deza Luna
Doutor em Processos de Fabricação pela Universidade Federal do Rio Grande do Sul, Porto Alegre, Brasil
Faculdade de Tecnologia SENAI CIMATEC

____
Charles Chemale Yurgel
Doutor em Processos de Fabricação pela Universidade Federal do Rio Grande do Sul, Porto Alegre, Brasil
Faculdade de Tecnologia SENAI CIMATEC

____
Ivo Andrei Oliveria Lino Lima
Doutor em Modelagem Computacional e Tecnologia Industrial pelo SENAI-CIMATEC, Salvador, Brasil
Faculdade de Tecnologia SENAI CIMATEC

19/09/2016

AGRADECIMENTOS

O presente trabalho foi desenvolvido em parceria com a faculdade Hochschule Aalen für Technick und Wirtschaft na Alemanha, como parte da experiência internacional do programa de programa Jovens Talentos do Instituto SENAI de Inovação em Conformação e União de Materiais. Sua conclusão não teria sido possível sem a ajuda de:

Dr. Eng. Charles Chemale Yurgel e Dr. Wilberth Harold Deza Luna, pelas orientações neste trabalho;

Toda equipe da pós-graduação em Conformação e União de Materais do SENAI-BA;

Meu orientador na Alemanha, Prof. Dr. Ing- Harald Riegel;

Toda equipe do mestrado em Photonics da Hochschule Aalen für Technick und Wirtschaft;

Aos professores e orientadores que fizeram parte dessa jornada, assim como aos idealizadores do programa;

A todos os colegas do SENAI CIMATEC e do curso de Pós-graduação pelos longos momentos de estudo e companheirismo.

Abstract

In this paper the gap bridging ability of a 4 kW Nd:YAG laser while welding two types of aluminum is studied: cast alloy AlSiMg10 and wrought alloy AlMg4.5Mn0.4. The samples had constant growing gap that reached a maximum of 1.5 mm and 1.0 while having a 1.5 mm thickness and 2.0 mm gap while having a 6.0 mm thickness. Welds, both with and without filler wire, were produced by varying laser power, welding speed, filler wire feeding speed and defocus. The parameters were tuned aiming to achieve a good weld surface quality and an optimum amount of heat into the weld pool. The found results are that aluminum suffers considerably with sagging because of the low viscosity of its liquid phase. When defocus is increased no increased gap bridging was observed as the sagging phenomenon was also increased due to the higher amount of base material melted. Ideal parameters were found for each type of sample.

Keywords: gap bridging, aluminum, laser welding

Resumo

No presente trabalho a habilidade de soldar com espaçamento entre as peças foi avaliada utilizando um laser de Nd:YAG com 4 kW de potência máxima em dois tipos de alumínio: liga fundida AlSiMg10 e liga forjada AlMg4.5Mn0,4. As amostras possuiam um espaçamento crescente até os máximos de 1,0 mm e 1,5 mm para a espessura de 1,5 mm e até o máximo de 2,0 mm para a espessura de 6,0 mm. Soldas, com e sem a adição de fio de enchimento, foram produzidas variando a potência do laser, velocidade de solda, velocidade do fio de enchimento e a posição do foco. Os parâmetros foram escolhidos visando atingir a melhor qualidade da superfície e transferência ótima de calor para o cordão de solda. Os resultados indicam que o alumínio sofre consideravelmente mais para soldar com espaçamento, pois devido à sua baixa viscosidade na fase líquida o material cede muito rapidamente. Desfocar o laser não foi capaz de produzir bons resultados, pois o fenômeno de decaimento na fase líquida foi ampliado devido à maior quantidade de material base fundido. Parâmetros ideias foram encontrados para cada tipo de amostra.

Palavras-chave: solda com espaçamento, alumínio, solda a laser

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1 Introduction

Laser welding is a relatively new process compared to other better established welding processes; however it has recently been receiving growing attention from the industry, especially in the automotive and aerospace fields (MATHERS, 2002). Since it is a high energy-density and low heat-input process, many advantages arise, such as high welding speed and narrow heat-affected zone. The laser welding of aluminum presents special challenges, due to the material high reflectivity and high thermal conductivity. These characteristics, among others, have for a long time prevented the achievement of consistent weld quality when utilizing aluminum alloys (MATHERS, 2002). Due to its relative young age and inherent difficulties, aluminum laser welding is an open field for studies, with many process improvements and best parameters yet to be determined.

The laser beam has a small focused spot size, which produces a narrow weld with low distortion. On the other hand, the small size of the spot restricts the process tolerance to joint geometry, reducing considerably the flexibility. Previous studies results show that the use of a filler wire increases gap tolerance considerably, provided that a proper alignment between beam and wire is assured (AALDERINK, PATHIRAJ e AARTS, 2009). With good parameters, laser welding can be utilized efficiently in industrial applications, as for example the Audi A2, which had more than 30 meters of laser welds in its bodywork (MATHERS, 2002). The current study aims to identify optimal parameters in order to increase the ability to weld larger gaps in aluminum, utilizing the laser equipment available in the Hochschule Aalen, ensuring that the welds produced have enough quality in order to be used in most industrial applications.

2 Project Plan

The current project aims to study the ability of bridging gaps while welding aluminum alloys utilizing laser welding equipment. The influence of several parameters shall be investigated, such as laser power, defocus, welding speed and also the use of filler wire and its feeding velocity. The first step is to find a good set of initial parameters that will not be changed in the main study, which will be accomplished by a series of pre-experiments around the same setup without concern to gap bridging. The main group of experiments is then executed, initiating without the use of filler wire and later the influence of filler wire and its parameters shall be investigated. When all the samples are produced, they will go through metallographic analysis in order to assure that a minimum quality was achieved with the weld, according to the ISO 13919. In the end the results shall be discussed and an overview and outlook will be provided.

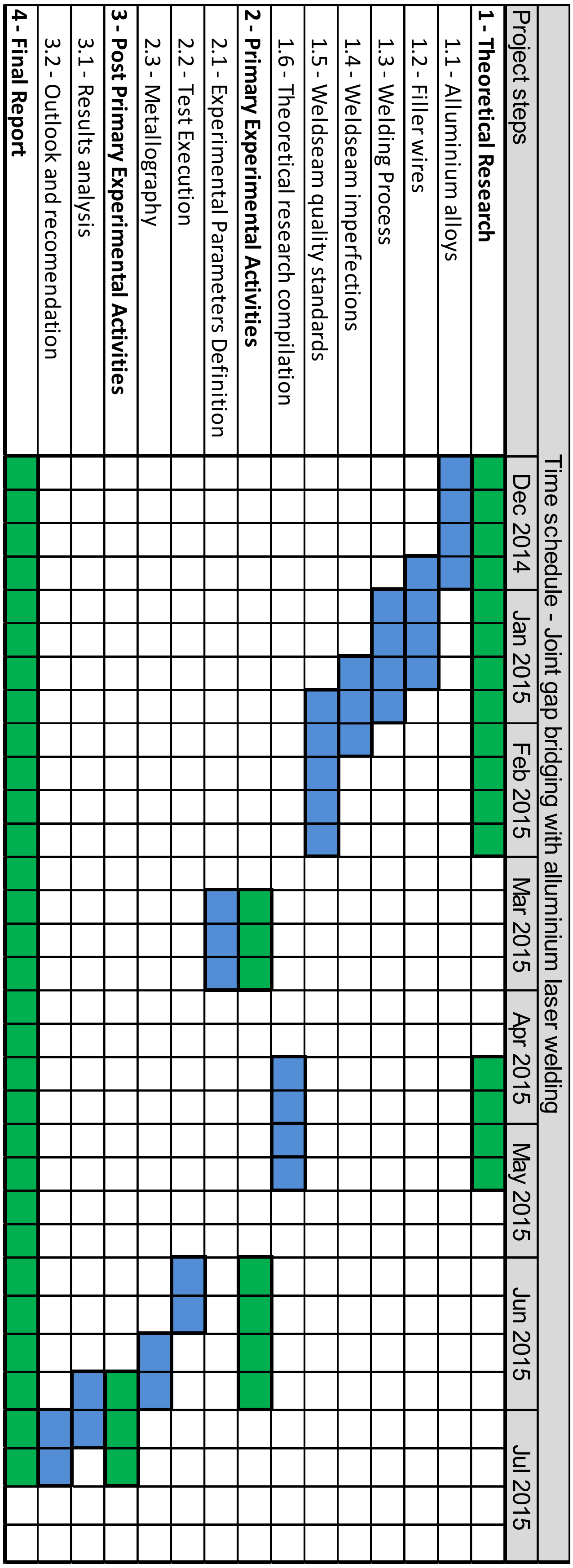

Figure 1: Time schedule

3 Theoretical Research

3.1 Welding Process

Laser welding is one of the main welding processes available for industry today and specially in the future. The high power density achieved with the focused laser beam allows for deep penetration with a small heat affected zone, rendering the process extremely suitable for many applications. High productivity, high weld quality, high welding speed, high weld aspect ratio, low heat input, low distortion and ease of automation can be achieved when comparing to other joining methods (DULEY, 1999) (MANDAL, 2001).

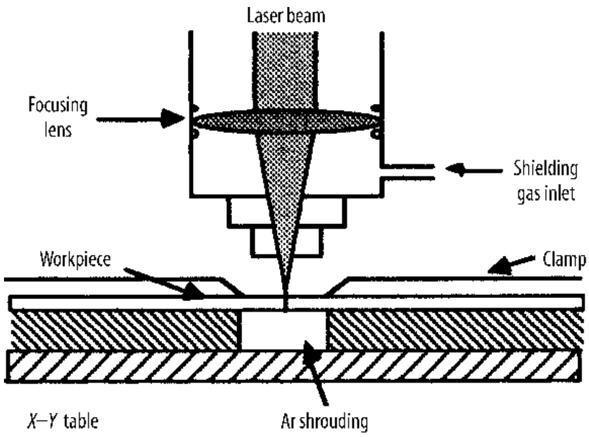

Figure 2: General Laser Welding setup (Steen & Mazumder, 2010)

Two welding modes can occur in laser welding, namely heat conduction welding and deep penetration welding. The first occurs at lower laser power or at higher welding speeds and the heat conduction energy transfer process dominates. The power density is not enough to cause boiling; therefore the result is characterized by a shallow pool of molten material. Deep penetration welding, on the other hand, has enough energy density to vaporize the material, effectively causing a hole in the weld pool. This mode allows for a much better absorption of the energy, effectively increasing the absorption from around 3 to 98% (STEEN e MAZUMDER, 2010). Since deep penetration welding results in better energy efficiency, larger depth to width ratios, smaller heat affected zone and less distortion, it is the most used method in the industry. It is important however, that a stable keyhole is maintained during the welding process. Literature recommends that the focus position should not change more than one millimeter in both directions in order to achieve stable keyhole and to prevent lack of fusion. The laser welding head angle is also important in order to ensure stable keyhole and should be kept as close to full vertical position as possible. Thin materials can we welded in a larger tilted angle because heat conduction welding process dominates (BACHHOFER, 2000).

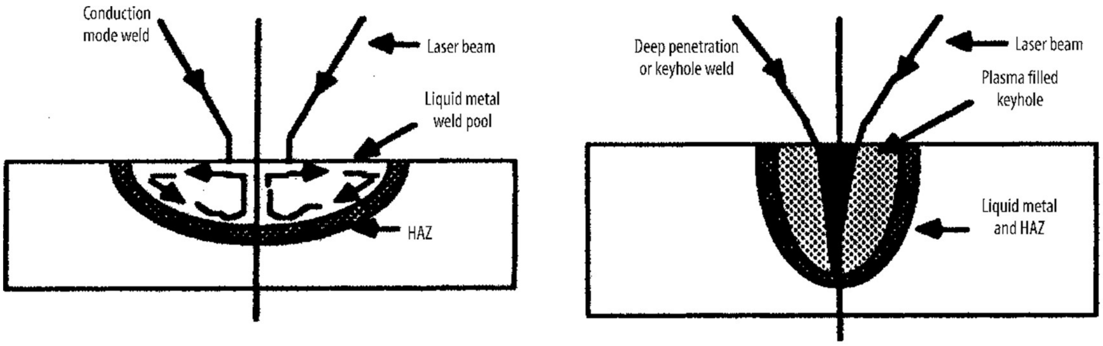

Figure 3: Heat conduction welding and deep penetration welding
(Steen & Mazumder, 2010)

The process of welding aluminum presents additional difficulties in relation to other more common metals because of the inherent characteristics of the material. High reflectivity and high heat conductivity limited aluminum laser welding for many years, yielding in a costly and problematic process. With the advent of high power lasers with better beam qualities, keyhole welding can be achieved and a higher coupling efficiency of energy to the weld seam is possible. However, many other characteristics still negatively influence aluminum welding, rendering it one of the most challenging materials to weld (MANDAL, 2001).

3.2 Aluminum Alloys

Aluminum is a metal that holds diverse strong properties to the manufacturing of products in the current world industry. A strong corrosion resistance and a relative light weight compared to other metals are two of many important characteristics that make aluminum widely used globally. Other important characteristics of aluminum include its high versatility and machinability, being able to be cast in any form or stamped, drawn, rolled, spun, hammered and forged with great results. It also responds very well to extrusion, milling and turning (MATHERS, 2002).

Even though it is the third most abundant metal in the Earth's Crust, aluminum in its pure form is too soft for many applications. To overcome this characteristic, many alloying elements are used. The most common ones are copper, manganese, silicon, magnesium and zinc. Adding copper to the aluminum increases the material strength, but may reduce ductility and corrosion resistance. One of the biggest problems with these alloys is the significant increase in susceptibility to solidification cracks, rendering them rather challenging to weld. Addition of manganese provides moderate strengthening through solution hardening without affecting significantly ductility and corrosion resistance. Silicon reduces melting temperature and enhances fluidity. In combination with magnesium produces magnesium-silicide (Mg2Si). This compound provides heat-treatability. The addition of magnesium increases strain hardening ability through solid solution strengthening. These constitute non-heat-treatable alloys with highest resistance, being widely used for structural applications. Zinc addition substantially increases strength and permits precipitation hardening, producing the highest strength heat-treatable alloys when used in conjunction with other elements (How and why alloying elements are added to aluminum, 2014).

Figure 4: Alloying element influence in aluminum. Source: Aluminiumdesign.net

3.3 Filler Wires

Laser beam welding is a process that allows for autogenous welding, which in many cases is considered a positive feature. However there are situations who find many advantages in using filler wires. By choosing specifically the composition of the filler wire to be used, it is possible to reduce the sensitivity to hot cracking in the weld pool area. Copper, silicon or magnesium can significantly reduce the occurrence of solidification cracks. It is also possible to compensate the loss of alloying elements. Laser beam welding is a process that requires precise fit up in order to achieve good welding quality; therefore many joint positions cannot be achieved without compromising the weld area properties. Filler wires can allow for larger gap between the parts, granting higher flexibility to the process and can also help prevent excessive seam concavity, by making a larger weld top which will later be grinded (BACHHOFER, 2000). Choosing the optimal filler wire to be used depends on the interaction between the alloy used for filler wire and the base alloy. The final application of the piece can require specific properties which have to be taken into consideration in the moment of choice. More information about choosing the correct filler wire can be found on the appendix.

Although the use of filler wire increases the flexibility of the joint allowing for larger gaps, it also increases the complexity of the welding process. Aside from the selection of the optimal filler wire material, which requires taking into consideration many factors such as crack resistance, corrosion resistance, strength, appearance, among others, the engineer responsible also have to ensure that the positioning of the elements during the welding procedure is precise. Previous studies, utilizing scanning lasers, have shown that for gaps of 1.0 mm in butt welding, the position of the filler wire must not exceed 0.35 mm in the direction of the beam or 0.2 mm in the pieces direction in order to achieve good quality weld (SEEFELD, 2014). Processes without using scanning lasers should have even smaller tolerance.

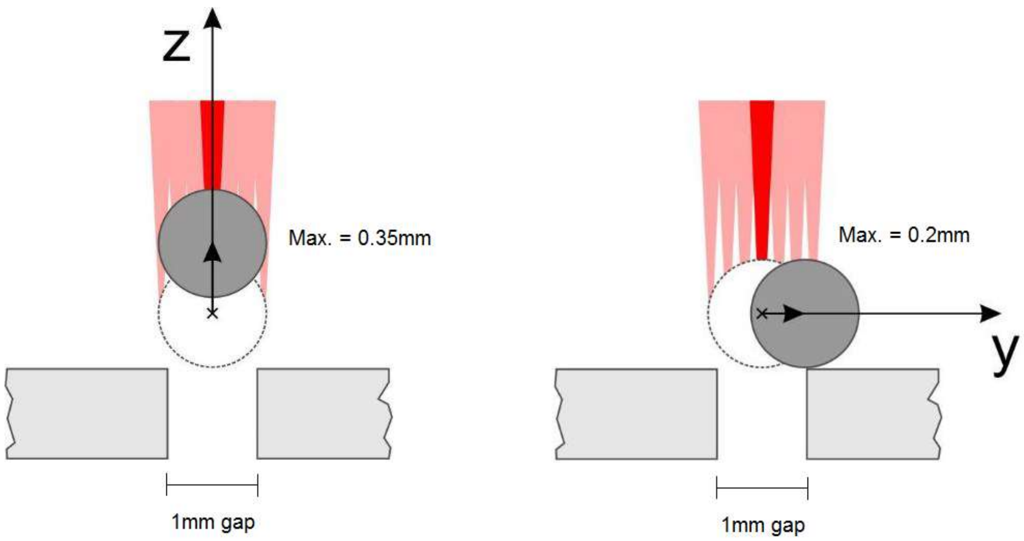

Figure 5: Filler wire positioning tolerance (Seefeld, 2014).

Since the filler wire is coiled in its fabrication process, a rotational motion can occur during the wire feeding due to internal residual stresses. To reduce this effect, the filler wire feeding nozzle should be as close as possible to the part, in order to reduce the lever arm. Literature recommends that the filler wire should be as close as possible to the welding part; however the laser power utilized can limit this distance. For better results, this distance should be between 4 and 10 mm and the wire should not go into the work piece for more than half its diameter (BACHHOFER, 2000).

When utilizing filler wire the amount of material to melt increases, meaning that in order to get the same amount of heat into the base material as without filler wire, the speed needs to be reduced. This effect is enhanced when the procedure requires small welding speeds; reductions of 75% can be recommended when utilizing filler wire, whereas at faster procedures 10% speed reduction is sufficient. When welding at higher speeds less heat goes into the parts, generating a smaller weld seam that requires less filler wire (BACHHOFER, 2000).

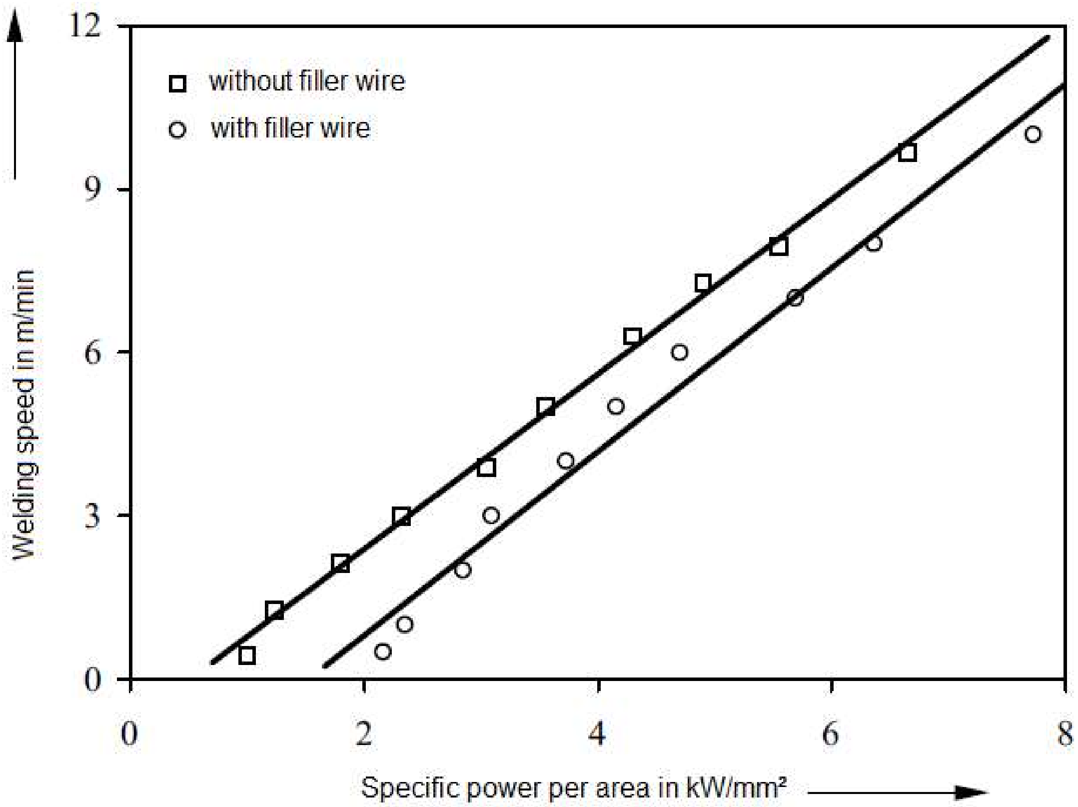

Figure 6: Energy comparison between autogenous and filler wire welding in regard to welding velocity (BACHHOFER, 2000)

Regarding the filler wire entrance angle in the part, if weld is made with pulling position and welding at 90 degrees, the recommended value is 35 degrees, with the variation being possible between 15-50 degrees. When choosing the filler wire diameter, the following relation must be observed:

$$d_{fw} = 3 \cdot d_{ls}$$

Where d_{fw} is the filler wire diameter and d_{ls} is the laser spot diameter. Another important relation governs the filler wire feeding velocity :

$$v_{fw} = W \cdot \frac{v_{ws}}{{d_{fw}}^2}$$

$v_{fw} = filler\ wire\ feeding\ velocity$
$W = weld\ seam\ fill\ factor$
$v_{ws} = welding\ speed$
$d_{fw} = filler\ wire\ diameter$

The weld seam fill factor is dependent on the type of joint to be welded and the size of the gap. For a butt weld and a gap of 0 mm, the value for W should be 0.9 mm^3/mm. For increasing gap, this value needs to be increased between 0.8 and 1.2 mm^3/mm (BACHHOFER, 2000). In the appendix it is possible to find common values of the weld seam fill factor for different joint types.

3.4 Weld Seam Imperfections

When welding aluminum, four major defects occur with relative frequency: porosity, hot cracking, inclusions and loss of alloying elements (MATSUNAWA, 1994).

Porosity consists of gas bubbles that remain trapped in the weld seam area after solidification. In the case of aluminum, most of the porosity comes from hydrogen bubbles, because hydrogen has a high solubility in liquid aluminum but very low in solid aluminum. This issue is even further increased when laser welding is the chosen process; due to the high temperatures, hydrogen solubility is increased and the cooling rate is very large, which reduces the time available for the gas diffusion to occur. It is also known that porosity tends to increase when filler metal is used instead of autogenous welding, due to contamination from the wire (MATHERS, 2002). In situations where many measures are taken to prevent the contamination of the weld seam by hydrogen, another kind of porosity is still observed when performing laser welding (Weeter, 1998). These concentrate more around the keyhole path instead of being equally distributed and their generation is attributed to keyhole instability (PASTOR, ZHAO e MARTUKANITZ RP, 1999).

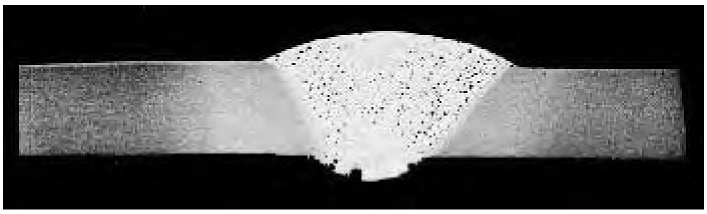

Figure 7: Porosity in aluminum alloy (Mathers, 2002)

Hot cracking is a phenomenon that occurs during the solidification process of metals, where gaps (cracks) appear in the material due to the volume reduction. Laser welding of aluminum is particularly susceptible to hot cracking due to the high thermal coefficient of expansion. Many measures can be taken to eliminate hot cracking: reducing grain size, adding specific filler metals to the weld pool, increasing welding speed and applying an external force to maintain the weld in compression during solidification are examples (MATHERS, 2002).

The most common type of inclusion in aluminum alloys are oxides. Imperfect or impure shielding gas can contain oxide particles, which get trapped in the weld seam during the welding process. It is worth mentioning that the content of magnesium in the alloy affects the tendency to formation of oxide inclusions, due to the rapid formation of magnesium oxide (MgO) and the use of filler wires can have an impact on the occurrence of inclusions (Tu & Paleocrassas, 2010).

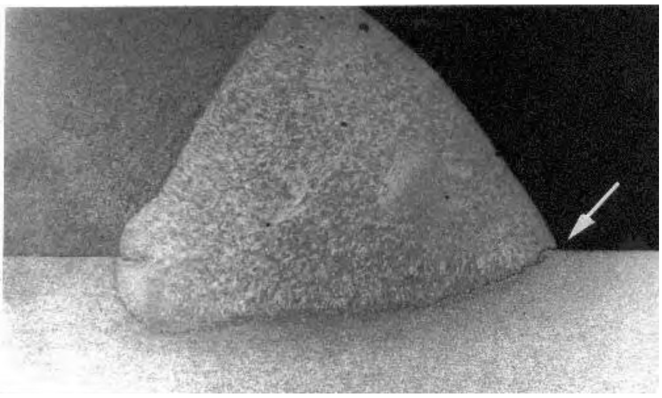

Figure 8: Oxide inclusion (Mathers, 2002)

Laser welding is a process with very high power density, having enough energy to vaporize metals. If the alloy possesses metals with relative lower fusion point, these may selectively vaporize, changing the composition of the weld seam area. Two possible ways to control loss of alloying elements are to utilize filler metal (Ion, 2000) and ensuring stable keyhole (Mathers, 2002).

When performing welding procedures, a few defects are of common reoccurrence. These are classified according to their appearance and not according to their origin by the standard DIN 8524. When performing gap bridging procedures, some of these defects require special attention. Lack of fusion, as the name implies, occurs when metal is left incompletely or insufficiently molten in the weld seam area. This can occur when the gap is too large and the region of the beam that is in contact with the material does not have enough energy to melt the metal. Lack of penetration is a similar problem, where the weld does not go deep enough into the material in order to provide the mechanical properties required to the weld seam.

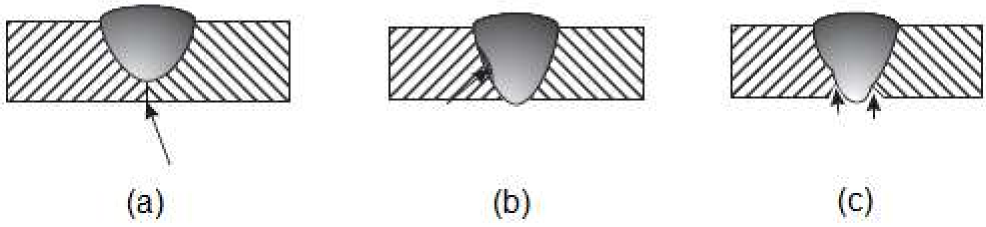

Figure 9: (a) Lack of penetration; (b) Lack of fusion between weld and base metal; (c) Lack of fusion on weld root. (ISF-Aachen)

If the process parameters are not correctly tuned, root relapse or seam concavity can occur. These can be observed in Figure 10 (b) and (c). Depending also on the parameters and welding setup, it is also possible that metals with low viscosity in the liquid phase flow down due to gravity during the welding procedure, producing a curved shape in the region. The resulting weld seam for this phenomenon can be seen in Figure 10 (a). Poorly executed welding setup can also incur in edge notches or edge misalignment, which affects the properties of the final part directly. Illustrations of these defects can be seen in Figure 11 (a) and (b). If too much heat goes into the piece due to incorrect parameters, an excessive weld seam can occur. This can enhance problems that are caused due to welding, such as excessive bend or too large heat affected zone. An excessive weld seam can also render the piece unable to satisfy the strength requirements in the area. Figure 12 shows an illustration of such situation.

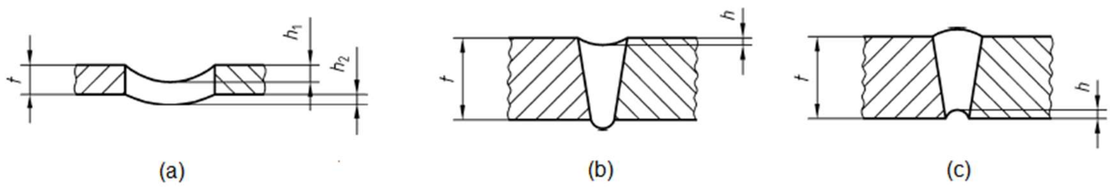

Figure 10: (a) Excessive liquid metal flow in direction of root; (b) excessive seam concavitiy; (c) excessive root relapse. (EN-ISO-13919-2, 2003)

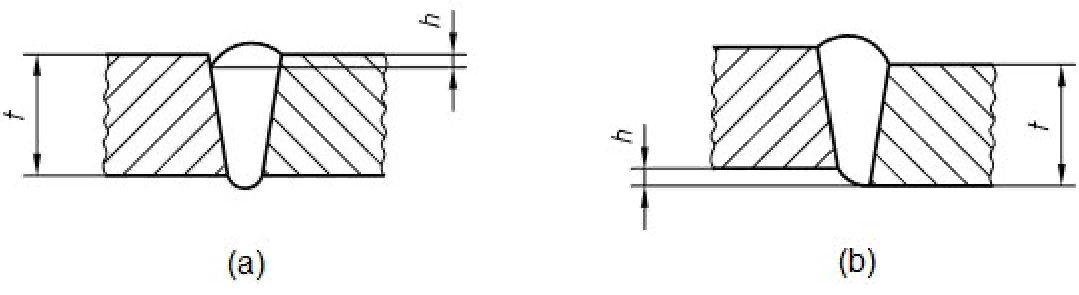

Figure 11: (a) edge notche; (b) edge misalignment. (EN-ISO-13919-2, 2003)

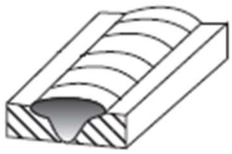

Figure 12: Excessive weld seam. (ISF-Aachen)

3.5 Weld Seam Quality Evaluation

The first step in the quality assessment is the visual inspection. Such procedure can reveal macro defects like cracks or holes. Typical defects related to aluminum laser welding and guidance related to the quality evaluation of such methods is defined in the international standard ISO 13919-2. Not all the imperfections defined in the standard are of equal importance to all applications and an assessment must be done in order to define what is most relevant. With the help of literature, the imperfections decided to be investigated in this project are cracks, holes and the geometric features of the bead, which are investigated with the definition of the following parameters: crown width, root width, fused area, excessive penetration, misalignment and sagging (Caiazzo, Alfieri, Cardaropoli, & Sergi, 2012) (Aalderink, Pathiraj, & Aarts, 2009).

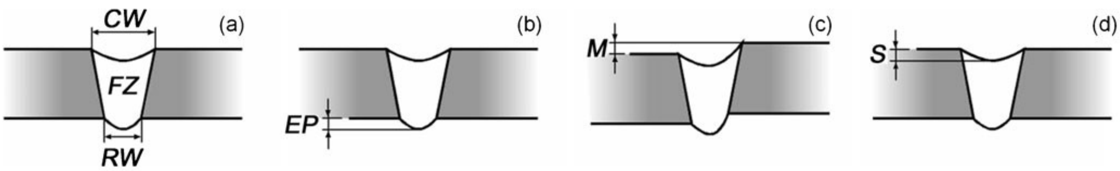

Figure 13: (a) geometric features, (b) excessive penetration, (c) misalignment, (d) sagging (Caiazzo, Alfieri, Cardaropoli, & Sergi, 2012)

Specific values for the accepted geometric features are not defined in the standard, however they are of interest in order to measure the amount of heat that was used in the material melting and thereby the process efficiency. For the excessive penetration, vertical misalignment of the welded parts and for excessive sagginess the tolerances for the measurements shown in figure 13 as defined in the standard are (in all cases t is the parts thickness):

	Low quality weld (D)	Middle quality weld (C)	High quality weld (B)
Excessive penetration or root reinforcement	EP ≤ 0.2mm + 0.3*t; max. 5 mm	EP ≤ 0.2mm + 0.2*t; max. 5 mm	EP ≤ 0.2mm + 0.15*t; max. 5 mm
Vertical misalignment	M ≤ 0.25*t; max. 3 mm	M ≤ 0.15*t; max. 2 mm	M ≤ 0.1*t; max. 1 mm
Excessive sagginess	S ≤ 0.15*t; max. 2 mm	S ≤ 0.1*t; max. 1.5 mm	S ≤ 0.05*t; max. 1 mm

Table 1: Tolerance values for weld seam characteristics. (EN-ISO-13919-2, 2003)

Porosity is also a major defect when laser welding aluminum alloys. It comes in the form of macro and micro porosities, with considerably different pore diameter. Macro porosities are associated with keyhole instability and can be observed by visual and microscopic inspection (Caiazzo, Alfieri, Cardaropoli, & Sergi, 2012) (Pastor, Zhao, & Martukanitz RP, 1999). Micro porosities are associated with inclusions and their isolated occurrence does not result in rejection of the parts (EN-ISO-13919-2, 2003). A proper analysis of micro porosities demands extensive time and falls out of the scope of this project. For critical applications that require controlled levels of porosity the weld seam quality evaluation performed in the current study is not sufficient.

4 Experimental Activities

4.1 Material used

Two kind of aluminum alloys were used as base materials. The first one is the cast alloy AlSi10Mg and the second is the wrought alloy AlMg4.5Mn0.4.

Fe	Si	Mn	Ni	Ti	Cu	Pb	Mg	Zn	Sn	Others
max 1.0	9.0 - 11.0	max 0.55	max 0.15	max 0.2	max 0.1	max 0.15	0.2 - 0.5	max 0.15	max 0.05	each 0.05; total 0.15

Table 2: AlSi10Mg Chemical Composition

The AlSi10Mg alloy has good casting properties and is many times used for parts with thin walls and complex geometry. While it can be machined, spark-eroded, welded, micro shot-peened, polished and coated when required, it is ideal for applications which require a combination of good thermal properties and low weight. (SYSTEMS, 2014). Al-Si alloys enable the precipitation of Mg2Si which enables the hardening of the material. Furthermore, it is relatively easy to process by laser applications due to the near-eutectic composition of Al and Si which is known to lead to a small solidification range (KEMPEN, L.THIJS, *et al.*, 2012).

Rm - Tensile strength (MPa)	$R_{p0.2}$ 0.2% proof strength (MPa)	A - Min. elongation at fracture (%)	Brinell hardness (HBW)
240	140	1	70

Table 3: AlSi10Mg Mechanical Properties

Tm - Melting Temperature ºC	Tb - Boiling Temperature ºC	Cp - Heat capacity J/(kg.K)	λ - Heat Conduction W/(m.K)
557 - 596	2500	878 - 1096	113 - 153

Table 4: AlSi10Mg Physical Properties

Fe	Si	Mn	Cr	Ti	Cu	Mg	Zn	Others
max 0.35	max 0.2	0.2 - 0.5	max 0.1	max 0.1	max 0.15	4.0 - 5.0	max 0.25	each 0.05; total 0.15

Table 5: AlMg4.5Mn0.4 Chemical Composition

The wrought alloy AlMg4.5Mn0.4 belongs to the 5000 family of alloys, which have as main alloy element magnesium. These alloys, specially the ones with manganese, give result to moderate to high strength materials, that possess good welding characteristics and good resistance to corrosion (MONDOLFO, 1943).

Rm - Tensile strength (MPa)	$R_{p0.2}$ 0.2% proof strength (MPa)	A - Min. elongation Lo = 50mm (%)	Brinell hardness (HBW)
255 - 315	110	11 - 13	69

Table 6: AlMg4.5Mn0.4 Mechanical Properties

Tm - Melting Temperature ºC	Tb - Boiling Temperature ºC	Cp - Heat capacity J/(kg.K)	λ - Heat Conduction W/(m.K)
585 - 640	2500	900	123

Table 7: AlMg4.5Mn0.4 Physical Properties

For the filler wires, two types of alloys are used: ER5183 and ER4145. Both are supplied by SAFRA SPA.

Fe	Si	Mn	Ti	Cu	Mg	Zn	Be	Others
max 0.4	max 0.4	0.5 - 1.0	max 0.15	max 0.1	4.3 - 5.2	max 0.25	max 0.0003	each 0.05; total 0.15

Table 8: ER5183 Filler Wire Chemical Composition

Fe	Si	Mn	Cr	Cu	Mg	Zn	Be	Others
max 0.8	9.3 - 10.7	max 0.15	max 0.15	3.3 - 4.7	max 0.15	max 0.20	max 0.0003	each 0.05; total 0.15

Table 9: ER4145 Filler Wire Chemical Composition

4.2 Equipment Used

All the experiments were conducted with the same equipment. The laser source is a TRUMPF DiskLaser 4002, using as cell the TRUMPF LaserCell TLC1005. After the welding, the samples were cut with a Struers Discotom-5 Cutting Machine and later chemically treated with NaOH (Sodium hydroxide) for better analysis. The microscope used was the Zeiss AXIO.Zoom V16.

λ - Wavelength (nm)	Pmax - Maximum Laser Power (kW)	M² - Beam quality (mm.mrad)	d - Beam diameter (μm)
1030	4	8	200

Table 10: Laser characteristics

4.3 Sample preparation

Samples of 6.0 mm thickness were produced for the cast alloy. The cutting was done with an automatic saw. In case of the wrought alloy, 1.5 mm thickness samples were produced using a wrought guillotine. The samples have an increasing gap that goes from 0 mm to 1.5 mm or from 0 mm to 1.0 mm in the wrought alloy and from 0 mm to 2.0 mm in the cast alloy. The technical drawing for the samples can be found in the appendix.

Figure 14: Cast alloy samples. Wrought alloy samples have the same design with different gap

The edges of both sample types were prepared utilizing CNC milling equipment and later softened with a flat file. Short time before the execution of the experiments the samples were cleaned with alcohol.

4.4 Initial Parameters Setup

Literature recommends focusing on the filler wire or a little bit over, however that could cause problems if the filler wire tip is too far away from the piece (BACHHOFER, 2000). Normally the best position is on the piece surface or a few millimeters inside in order to achieve best efficiency. Since with filler wire it is necessary to focus on wire, laser power has to be increased. Using filler wire can result in seam topologies that are comparable to welding with too large defocus on autogenous welds.

Pre-experiments showed that bending in the cutting process is an issue since the geometrical defect is increased when heat is injected into the material, therefore the mechanics in the weld pool become unstable and inconsistent results are possible. It is important to have a stable cutting procedure, especially with thin samples.

Three nozzle types for the shielding were studied: cross jet, FL and conical. Also various gas flux velocities were tried out. The decided parameters were: conical nozzle type with 20 L/min gas flux. A number of samples were made, observing the behavior of the material and giving ideas how it responds to changes in defocus and laser power. The samples were cut and analyzed with regard to weld surface quality and specific melt volume in order to understand the parameter influence. Only the wrought aluminum was pre-studied due to the low number of samples for the cast aluminum.

4.5 Main Gap Bridging Experiments

4.5.1 Cast alloys

The welding program was written in a manner that makes it possible to study varying parameters in the gap area. For the first 40 millimeters the parameters are constant, which corresponds to the sample area with no gap. In the next 55 millimeters it is possible to linearly change the parameters in order to evaluate the influence in the growing gap. This behavior is shown in figure 15.

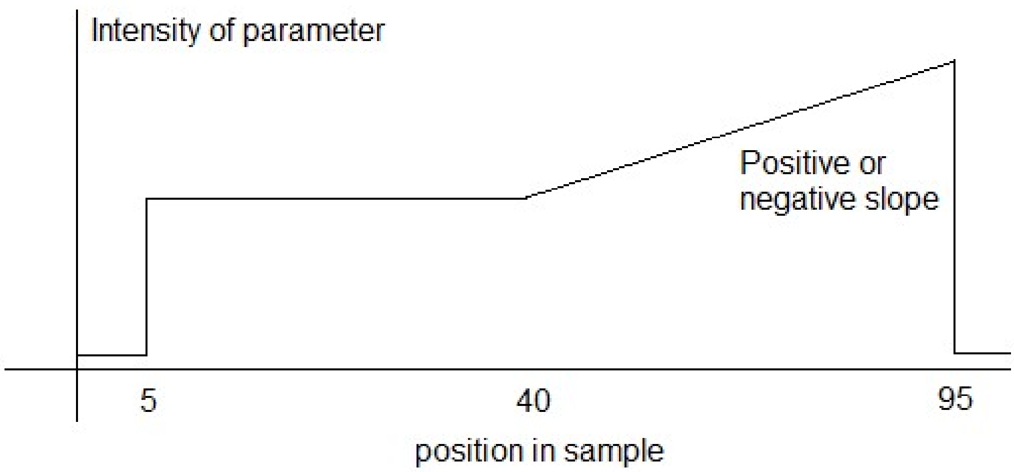

Figure 15: Possible parameter behavior in welding program

The number of samples for the cast alloy was limited; hence it was not possible to study a large number of parameters or a large range of values. Three samples were produced without the use of filler wire, studying the behavior of laser power. Parameters can be seen in table 11. Five samples were produced with the use of filler wire. Filler wire feeding speed and welding speed were varied searching for the best weld surface and largest gap bridging. Parameters can be seen in table 12.

Proc #	Type of aluminum	Welding Speed start (m/min)	Welding speed end (m/min)	Gap (mm)	Thickness (mm)	Focus (mm)	FW Speed start (m/min)	FW Speed end (m/min)	Laser Power (kW)
11	Cast	5	5	0 - 2	6	4	N/A	N/A	3
12	Cast	5	5	0 - 2	6	4	N/A	N/A	3,5
13	Cast	5	5	0 - 2	6	4	N/A	N/A	4

Table 11: Cast alloys without filler wire:

Proc #	Type of aluminum	Welding Speed start (m/min)	Welding speed end (m/min)	Gap (mm)	Thickness (mm)	Focus (mm)	FW Speed start (m/min)	FW Speed end (m/min)	Laser Power (kW)
18	Cast	4	4	0 - 2	6	4	4,166	4,166	4
19	Cast	4	4	0 - 2	6	4	4,861	4,861	4
20	Cast	4	4	0 - 2	6	4	5,555	5,555	4
21	Cast	4	4	0 - 2	6	4	4	8	4
22	Cast	2	4	0 - 2	6	4	4	10	4

Table 12: Cast alloys with filler wire

4.5.2 Wrought alloys

The program used for the wrought alloys was the same as the one used for the cast alloys, so the parameter behavior can also be changed in the same manner as described in figure 15. Initially the samples had 1.5 mm gap between them and eight samples were produced without filler wire. The influence of laser power was observed. Parameters can be found on table 13. After the initial laser power study, samples still with 1.5 mm gap were welded utilizing filler wire. Twelve samples were made by changing welding speed, laser power, filler wire feeding speed and defocus. The parameters for these samples can be found on table 14. The quality of the welds were evaluated by visual inspection after each sample was made and the parameters were adapted in order to improve the roughness, reduce sagginess and optimize the amount of heat into the weld seam.

Proc #	Type of aluminum	Welding Speed start (m/min)	Welding speed end (m/min)	Gap (mm)	Thickness (mm)	Focus (mm)	FW Speed start (m/min)	FW Speed end (m/min)	Laser Power (kW)
3	Wrought	1,5	1,5	0 - 1,5	1,5	8,5	N/A	N/A	1,25
4	Wrought	1,5	1,5	0 - 1,5	1,5	8,5	N/A	N/A	1,5
5	Wrought	1,5	1,5	0 - 1,5	1,5	8,5	N/A	N/A	1,75
6	Wrought	1,5	1,5	0 - 1,5	1,5	8,5	N/A	N/A	2
7	Wrought	1,5	1,5	0 - 1,5	1,5	8,5	N/A	N/A	2,25
8	Wrought	1,5	1,5	0 - 1,5	1,5	8,5	N/A	N/A	2,5
9	Wrought	1,5	1,5	0 - 1,5	1,5	8,5	N/A	N/A	2,75
10	Wrought	1,5	1,5	0 - 1,5	1,5	8,5	N/A	N/A	3

Table 13: Wrought alloys without filler wire

Proc #	Type of aluminum	Welding Speed start (m/min)	Welding speed end (m/min)	Gap (mm)	Thickness (mm)	Focus (mm)	FW Speed start (m/min)	FW Speed end (m/min)	Laser Power (kW)
23	Wrought	1	1	0 - 1,5	1,5	8,5	0,694	0,694	3
24	Wrought	1	1	0 - 1,5	1,5	8,5	1	15	3
25	Wrought	1	1	0 - 1,5	1,5	8,5	1,5	2	3
26	Wrought	1,5	1,5	0 - 1,5	1,5	8,5	1,5	2	3
27	Wrought	1,75	1,75	0 - 1,5	1,5	8,5	1,5	2	3
28	Wrought	2	2	0 - 1,5	1,5	8,5	1,5	2	3
29	Wrought	2	2	0 - 1,5	1,5	8,5	2	2,5	3
30	Wrought	2	2	0 - 1,5	1,5	8,5	2	2,5	3,5
31	Wrought	2	2	0 - 1,5	1,5	11,5	2	2,5	3,5
32	Wrought	2	2	0 - 1,5	1,5	11,5	2,5	3	3,5
33	Wrought	2,25	2,25	0 - 1,5	1,5	11,5	2,5	3	3,5
34	Wrought	2,25	2,25	0 - 1,5	1,5	11,5	3	3	3,5

Table 14: Wrought alloys with filler wire

During the weld of many samples, multiple retries were necessary due to instability of the filler wire. It was concluded that the final gap was too large in comparison to the thickness of the samples. Also the gap increase rate was too high, which was causing the filler wire to not properly attach to the base metal, causing unwanted dynamics in the weld pool. Because of that a new sample design was introduced, in which the gap goes from 0 to 1.0 mm. Twenty four welds were produced with the new design, utilizing three different focus positions. The complete parameters can be found in table 15.

Proc #	Type of aluminum	Welding Speed start (m/min)	Welding speed end (m/min)	Gap (mm)	Thickness (mm)	Focus (mm)	FW Speed start (m/min)	FW Speed end (m/min)	Laser Power (kW)
35	Wrought	1,5	1,5	0-1,0	1,5	8,5	1,5	2	3
36	Wrought	1,5	1,5	0-1,0	1,5	8,5	2	2,5	3
37	Wrought	1,5	1,5	0-1,0	1,5	8,5	2,5	3	3
38	Wrought	1,5	1,5	0-1,0	1,5	8,5	2	3	3
39	Wrought	1,5	1,5	0-1,0	1,5	8,5	2	3,5	3
40	Wrought	1,5	1,5	0-1,0	1,5	8,5	2	4	3
41	Wrought	1,75	1,75	0-1,0	1,5	8,5	2	4	3
42	Wrought	2	2	0-1,0	1,5	8,5	2	4	3
43	Wrought	2	2,5	0-1,0	1,5	8,5	2	4	3
44	Wrought	2	2,5	0-1,0	1,5	11,5	2	4	3
45	Wrought	2	2,5	0-1,0	1,5	11,5	2	4,5	3
46	Wrought	2	2,5	0-1,0	1,5	11,5	2,5	4,5	3
47	Wrought	2	2,5	0-1,0	1,5	11,5	3	4,5	3
48	Wrought	2	2,5	0-1,0	1,5	11,5	2,75	4,5	3
49	Wrought	2	2,5	0-1,0	1,5	11,5	2,5	5	3
50	Wrought	2,5	2,5	0-1,0	1,5	11,5	2,5	5	3
51	Wrought	2	2,5	0-1,0	1,5	14,5	2	4	3
52	Wrought	2,5	2,5	0-1,0	1,5	14,5	2	4,5	3
53	Wrought	3	3	0-1,0	1,5	14,5	2	4,5	3
54	Wrought	3	3	0-1,0	1,5	14,5	3	4,5	3
55	Wrought	3	3	0-1,0	1,5	14,5	4	4,5	3

Table 15: Wrought alloys with new smaller gap - with filler wire

5 Result Analysis

5.1 Cast alloys without Filler Wire

In these samples, laser power was varied. Since the thickness of the samples is very large, a high amount of energy would be necessary to weld completely through the material. Even though the current laser setup has a maximum laser power that is not big enough to provide an ideal weld, it is possible to see that increasing the energy provided to the parts in the case of the thick samples increased the gap bridging. Figure 16 shows a graph that relates the length of the weld in relation to the laser power and figure 17 shows a graph that relates the height of the weld in two positions (20 mm and 45 mm from the beginning of the sample) with the laser power.

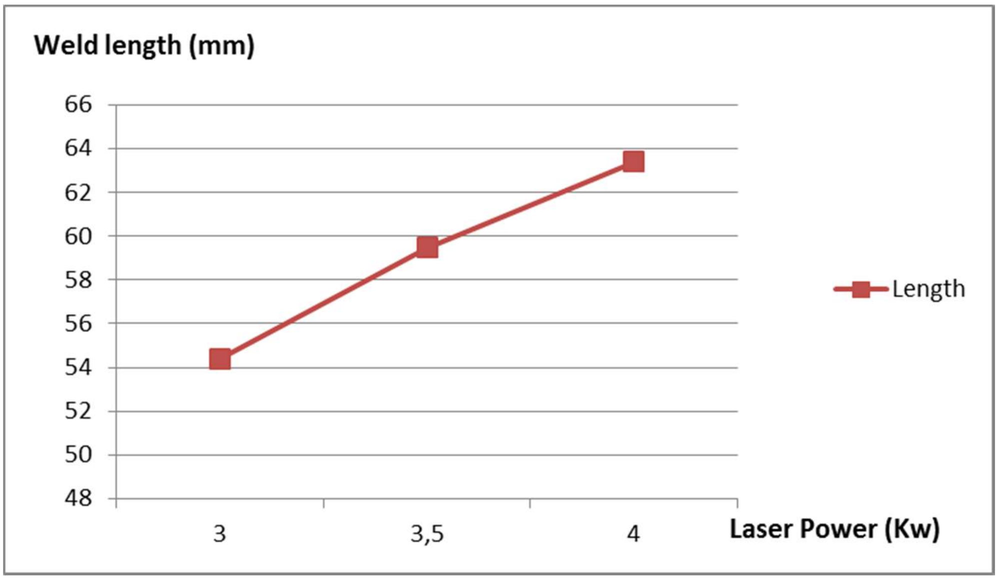

Figure 16: Weld length with increasing laser power

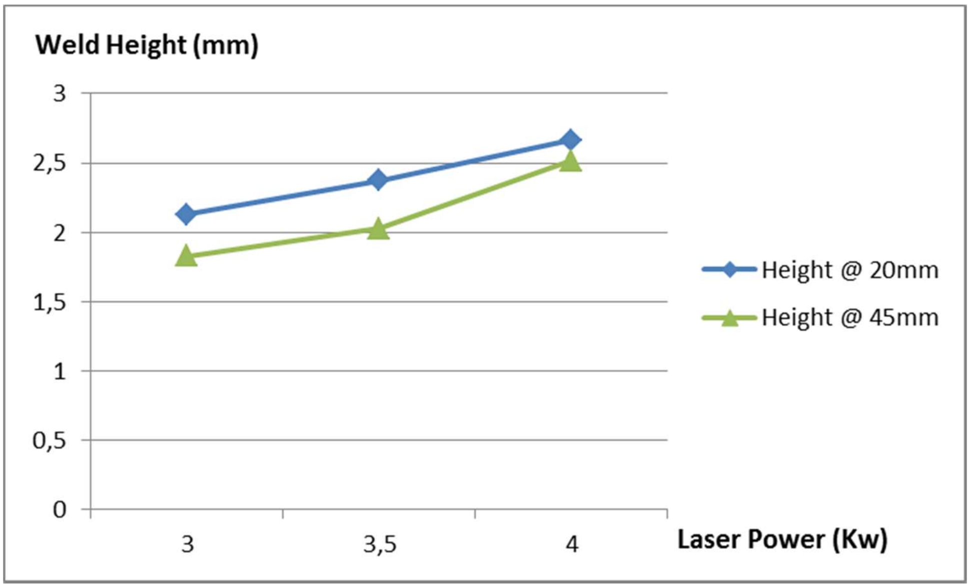

Figure 17: Weld height with increasing laser power at two positions

5.2 Cast Alloys with Filler Wire

In these samples the laser power was always kept at the maximum of 4 kW. The amount of filler wire was increased. It is possible to see that the sagging decreases when the amount of filler wire increases. The last available sample of cast alloy was welded with maximum laser power and with filler wire feeding speed growing until the maximum (10 m/min), resulting in the sample with less sagging in the gap area as shown by the profile analysis pictures. The deepest point of sample #18 which uses less filler wire is 607 micrometers below the surface whilst in sample #22 which uses more filler wire the deepest point is 305 micrometers below the surface. More power and more filler wire would certainly result in more gap bridging capability, however the limitations of the equipment available and the lack of cast alloy samples prevented these experiments to be conducted.

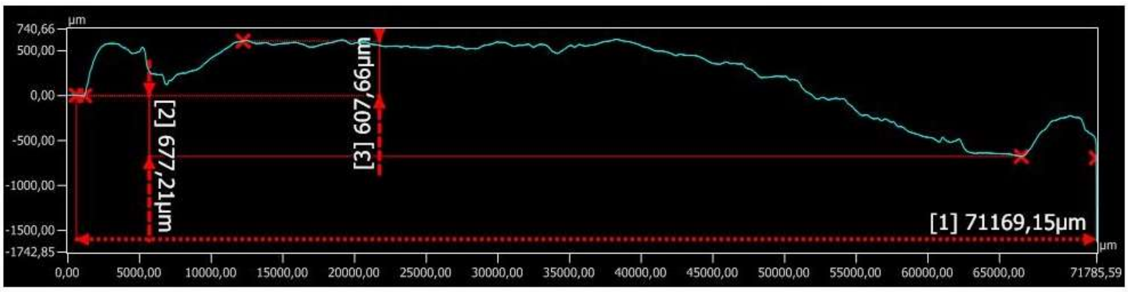

Figure 18: Sample #18 profile

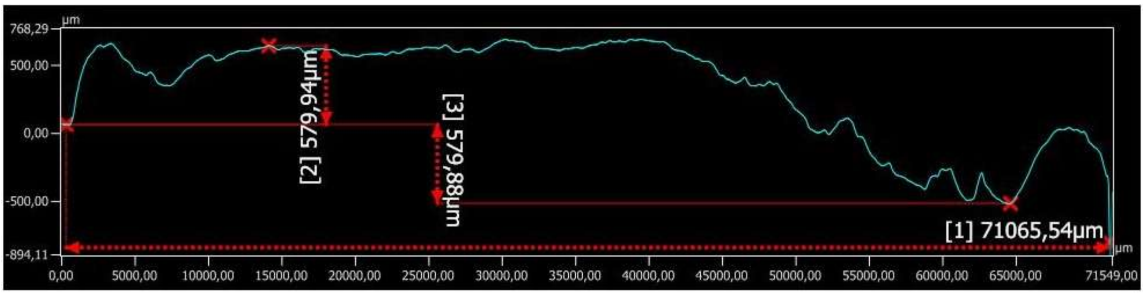

Figure 19: Sample #19 profile

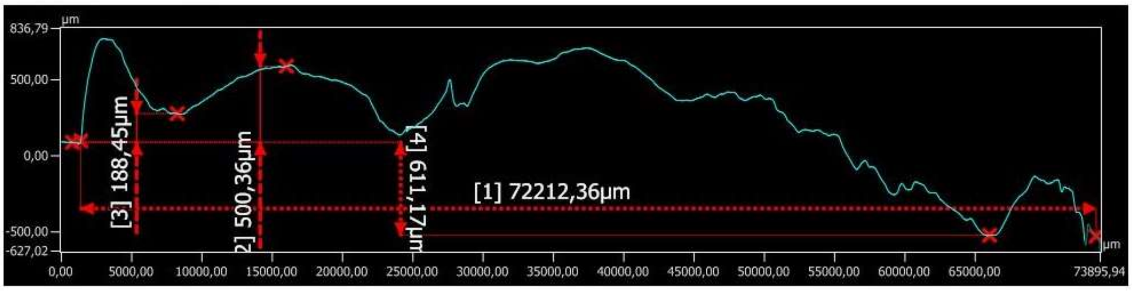

Figure 20: Sample #20 profile

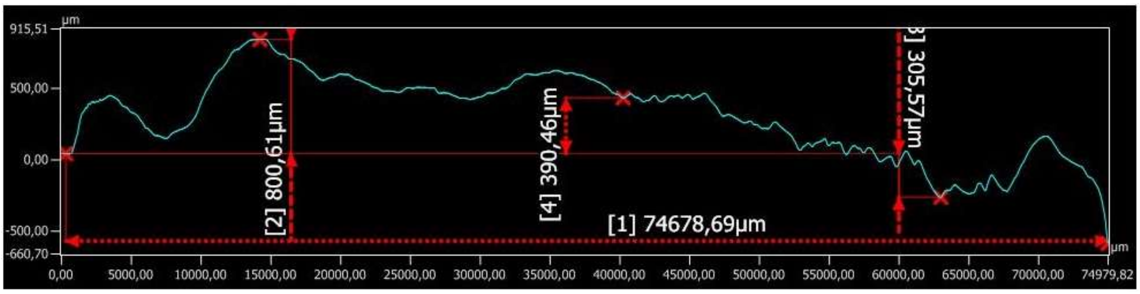

Figure 21: Sample #22 profile

The complete analysis profile for samples #18, #19, #20 and #22 can be found in the appendix. Also it was observed that the addition of filler wire increased the gap bridging ability; by comparing samples #22 and #13, both having the same power, when filler wire was used the weld total length was 73653.32 micrometers while without filler wire the weld failed after 63392.71 micrometers.

5.3 Wrought Alloys without Filler Wire

In these samples, laser power was varied. It was possible to see that with increasing laser power the gap bridging actually reduces, contrary to what was expected. This phenomenon is attributed to the high viscosity of the aluminum in liquid phase; when more power is used a larger part of the base material melts, which then flows down. This further increase the distance between the two base samples which disrupts the weld stability and causes the parts to lose contact even faster. Since in the case of the thin samples the heat is enough to heat the entire thickness of the material, there is no large solid material in the base to act as holder and the aluminum can flow down. Figure 22 shows a graph that relates laser power to the area melted and the height of the weld seam.

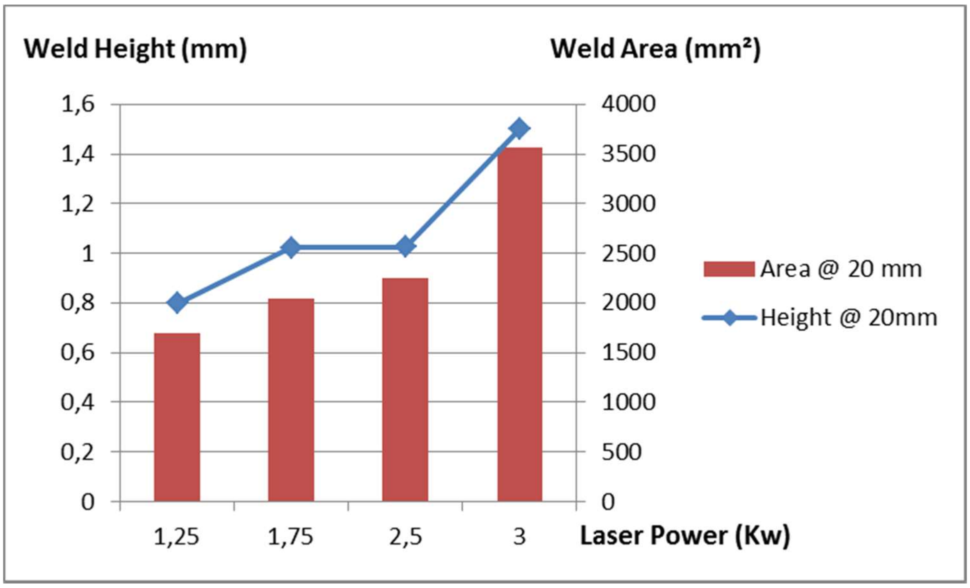

Figure 22: Area and height of cross section with regard to growing laser power

5.4 Wrought Alloys with Filler Wire and 1.5 mm gap

With the introduction of filler wire, more material has to be molten. Because of this, the initial welding speed for these samples was reduced. After that multiple values of filler wire feeding speeds and welding speeds were tried in order to achieve a good weld. Since the aluminum flows down in the liquid phase, it is very common to have a weld seam with very high degree of sagging. This issue can be solved by increasing the weld speed so the metal has less time to flow down or to increase the filler wire feeding speed, so that the extra metal can fill the hole. Another common issue is when the filler wire speed is too low in regards to the welding speed; the filler does not constantly supply metal to the weld seam causing the formation of bubbles on the tip that are dropped on top of the weld seam without having any real mixing with the base metal. This phenomenon can be observed on figures 23 and 24 where the bubbles can be seen with different spacing because of the increasing welding speed.

Figure 23: Bubbles with 1.75 m/min welding speed

Figure 24: Bubbles with 2.0 m/min welding speed

After finding the correct match between welding speed and filler wire speed, good top weld geometry was achieved in sample 29, however the back side was lacking penetration. Power was increased and sample 30 was considered the one to have better the best parameters for the 8.5 mm defocus.

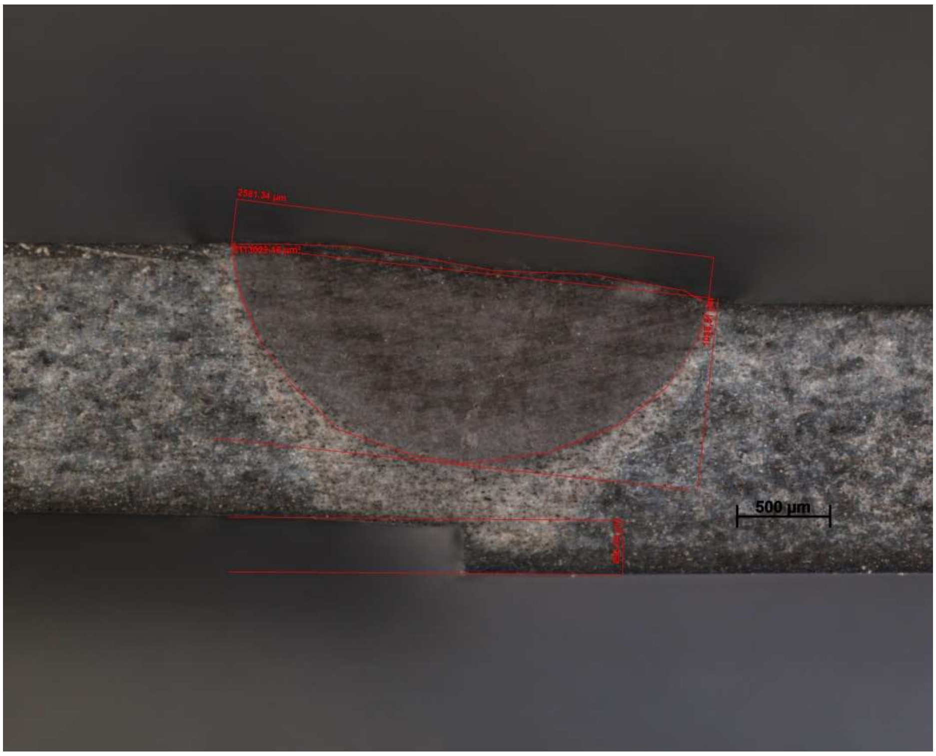

Figure 25: Sample #30 cross section @ 20 mm

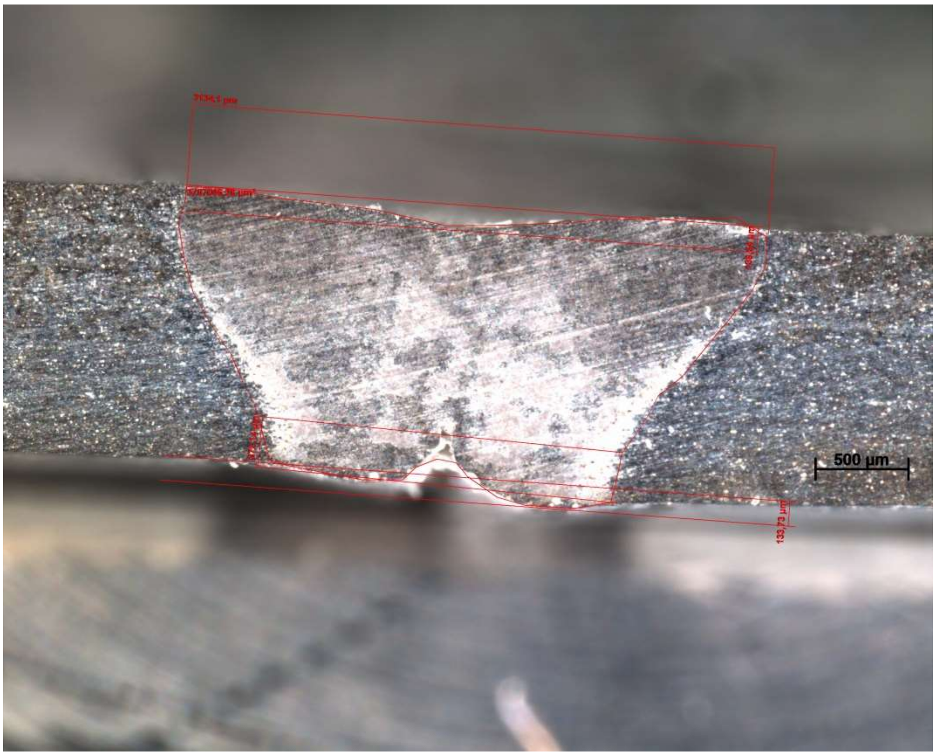

Figure 26: Sample #30 cross section @ 45 mm

Figure 25 shows the cross section of sample #30 at a position 20 mm into the weld seam, in the region where no gap was present. It is possible to see that the weld shows no sagging or excessive penetration and has the normal appearance of a heat conduction weld. It shows however a large misalignment which is attributed to the not ideal clamping conditions. Figure 26 shows the cross section of sample #30 at a position 45 mm into the weld seam. It is possible to see that a low degree of sagging is present which was measured to be 138.34 micrometers. Also it is possible to see root relapse of 272.14 micrometers due to the gap not being completely filled. Ignoring the misalignment defect cause by the poor clamping positioning this weld is categorized in the C quality and is therefore still possible to be used in the industry.

At this point the defocus was increased in order to study the influence in gap bridging. With a higher defocus more of the beam is inside the base material, heating a higher area. What was observed is that since more aluminum goes to the liquid phase the sagging phenomenon was further increased. Increasing the welding speed and the filler wire amount rendered no success, as the dynamics of the weld pool became very unstable and many retries were necessary to get constant results. At this point the samples had a gap of 1.5 mm which is the same size as the material thickness and the gap goes from 0 mm to 1.5 mm in a space of 50 mm. It was decided that the final gap was too big in comparison with the material thickness and that the gap growing rate was too large to keep the weld pool stable. New samples were produced that had a gap that goes from 0 mm to 1.0 mm in the same 50 mm space, reducing the final gap and the gap growing rate.

5.5 Wrought Alloys with Filler Wire and 1.0 mm gap

The new samples had a different geometry, so new good parameters had to be found. The same strategy as before was adopted, where the sagging and the bubbles were observed as the welding speed and filler wire feeding speed were varied, until a good plane stable weld seam was achieved in sample number 43.

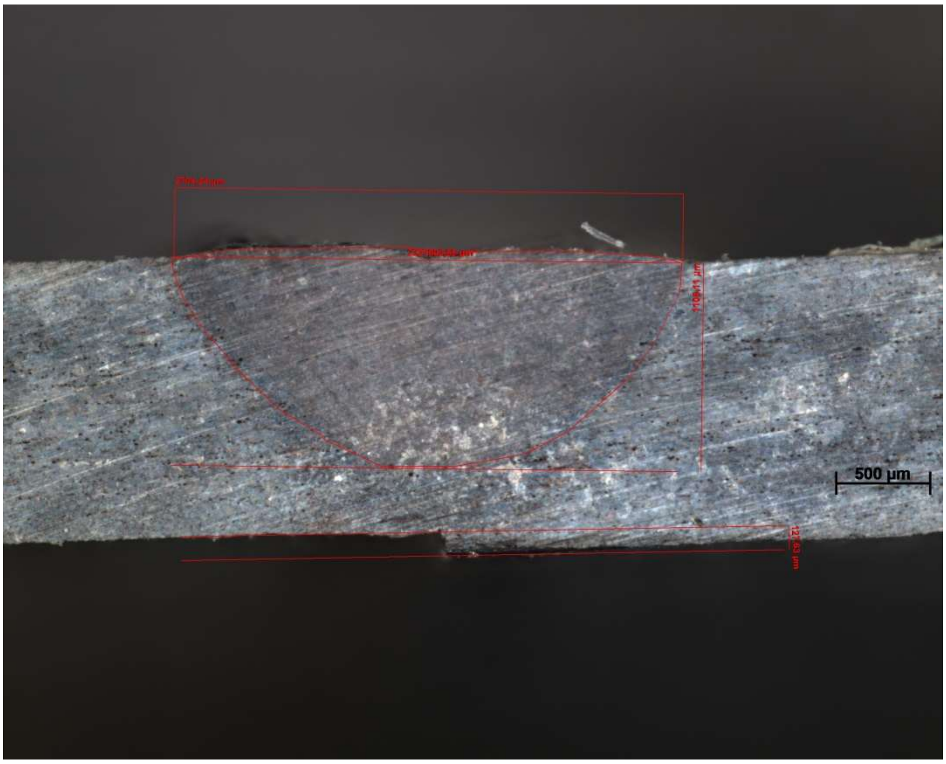

Figure 27: Sample #43 cross section @ 20 mm

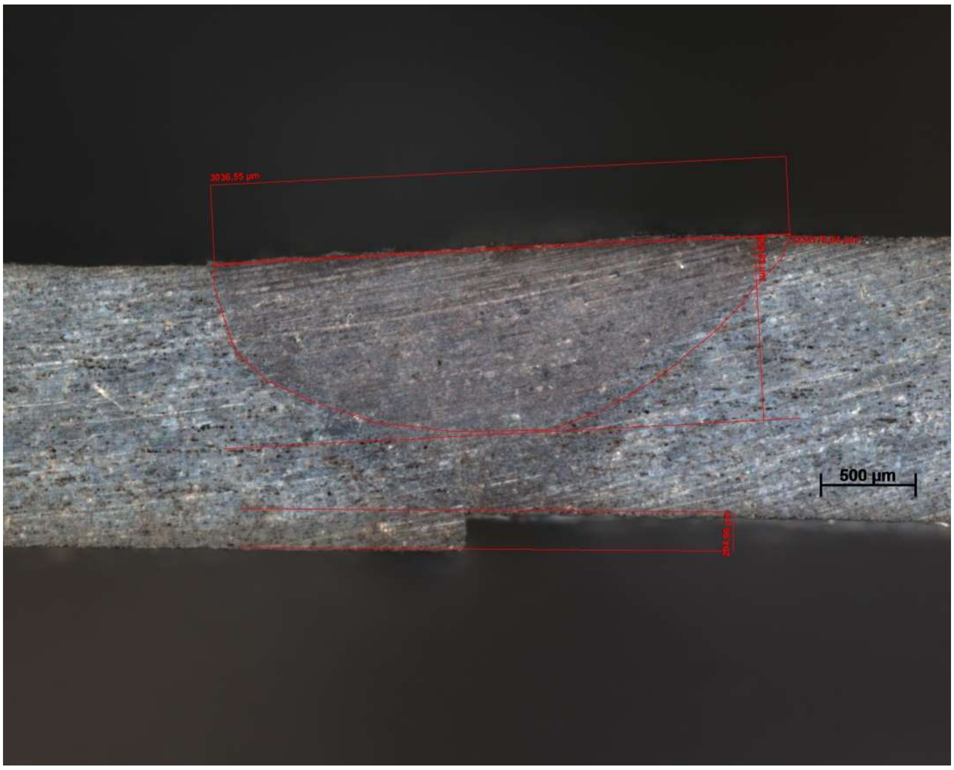

Figure 28: Sample #43 cross section @ 45 mm

Figures 27 and 28 show the cross sections of sample #43 at positions 20 mm and 45 mm. Both weld seams show no sagging or excessive penetration although a larger weld seam would be more ideal to increase mechanical properties. The high degree of misalignment is once again attributed to the poor clamping condition and is not related to the welding parameters. Keeping the same strategy as the older samples, defocus was increased to 11.5 mm in sample #44. The cross sections for this sample at positions 20 mm and 45 mm can be seen in figures 29 and 30. It is visible that just by increasing the defocus, sagging occurs.

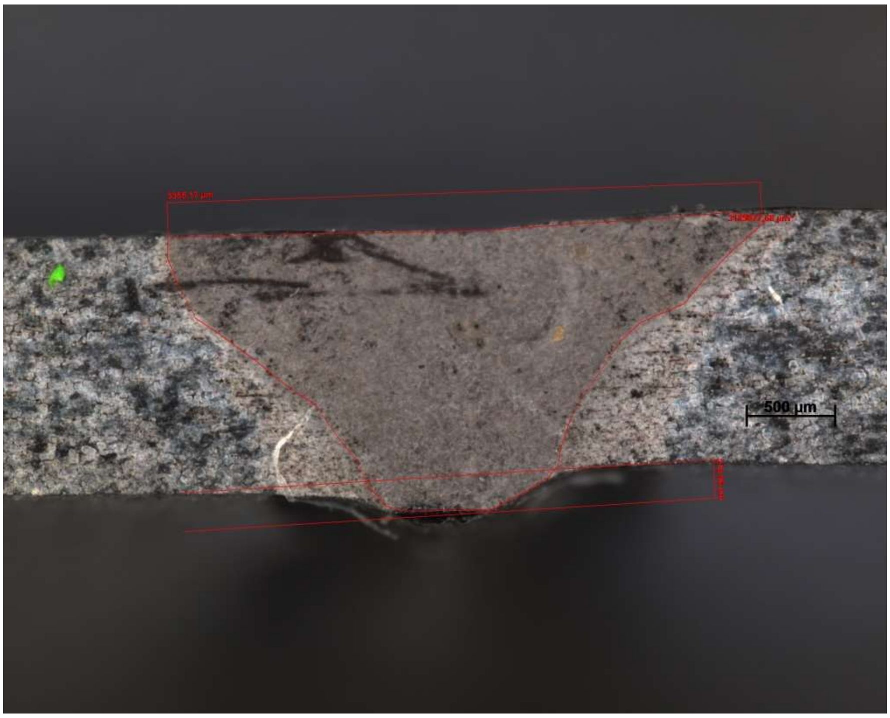

Figure 29: Sample #44 cross section @ 20 mm

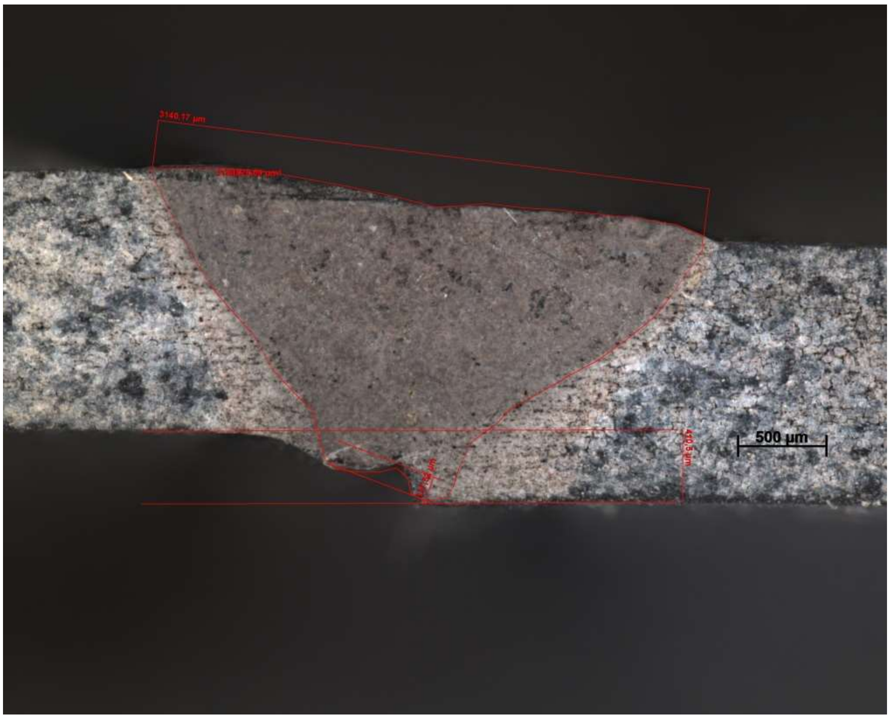

Figure 30: Sample #44 cross section @ 45 mm

Through six samples the filler wire feeding speed was varied rendering good and bad weld seams, however the gap bridging ability was not increased. The high viscosity represents a serious problem when the beam is too large such as in 11.5 mm defocused laser and for such a thin material there is a limit above which the welding speed cannot grow otherwise keyhole mode welding would occur, which is undesirable for thin samples. Therefore a point is reached that the welding speed is too low in order to prevent the material to flow down, but cannot be further increased otherwise a keyhole would be formed. In the last samples the defocus was further increased to 14.5 mm and the same behavior was observed. The cross sections for sample #54 can be seen in figures 31 and 32. One possible solution for this issue is using scanning laser heads, which can heat a higher base metal area but for a smaller time, reducing the sagging.

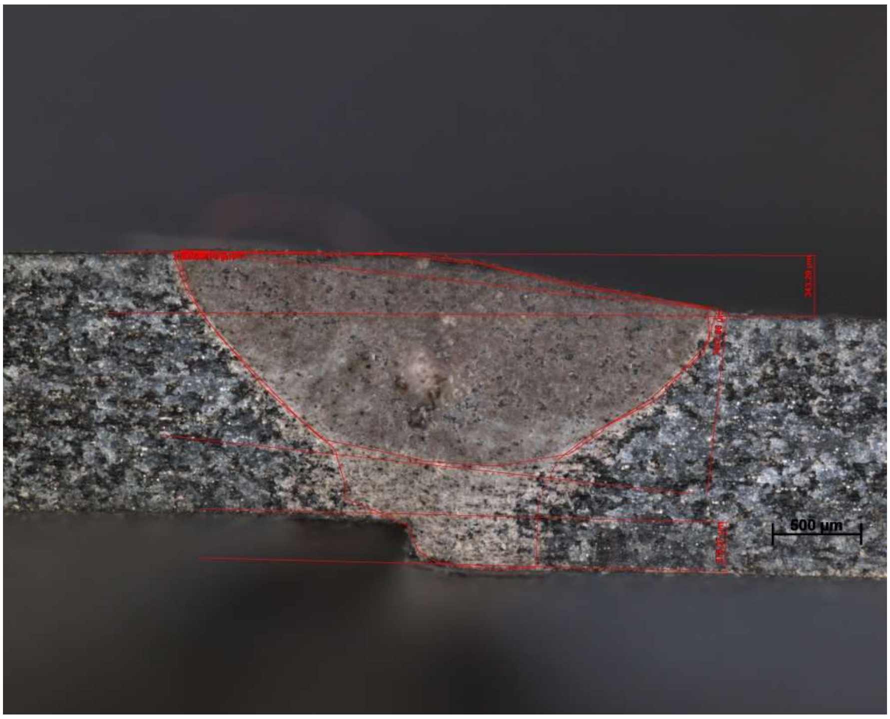

Figure 31: Sample #54 cross section @ 20 mm

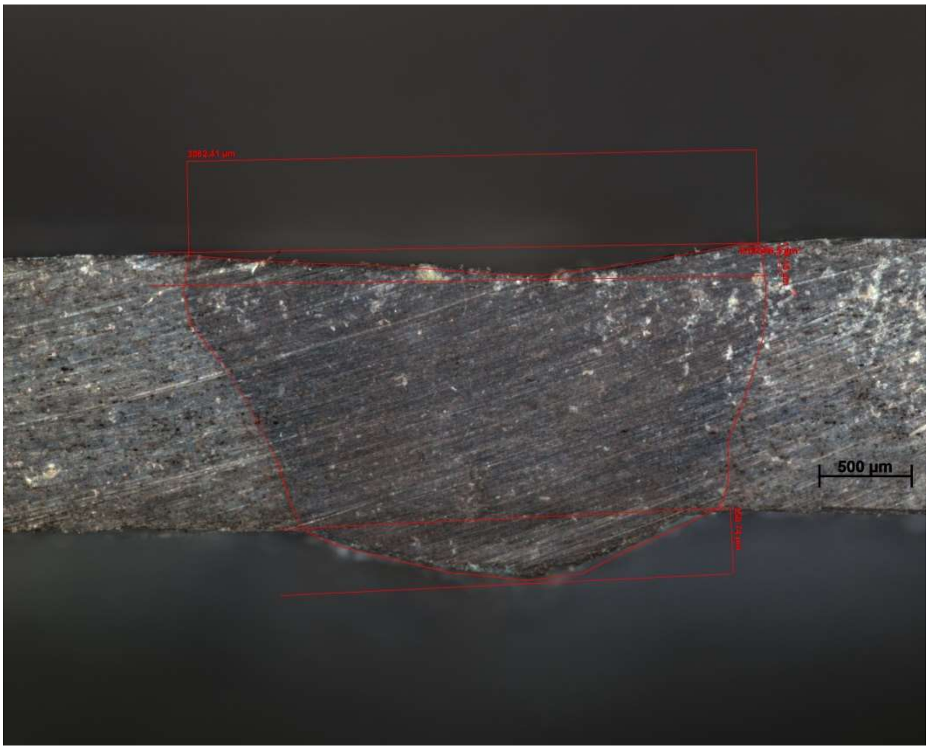

Figure 32: Sample #54 cross section @ 45 mm

5.6 Final Considerations

Gap bridging in aluminum alloys is a true challenge due to the characteristics of the material; the liquid phase must exist in the shortest possible time interval to avoid geometry changes. The use of a backing plate could give the process flexibility, however brings with it new problems in how to keep the process automatized and quick, which are great advantages of using laser welding. Thicker materials are more easily welded due to many factors. Less bending occurs when heat goes into the part, keeping the geometry constant and ensuring more stability. Less metal is molten in the lower area, preventing the flow down of the aluminum in the liquid phase. It is also possible to further increase welding speed reducing the molten material time to move. Thin material can only bridge a smaller gap due to not having these characteristics and for having less material to fill the gap area. Utilizing filler wire also increased the gap bridging ability, provided that the parameters were correctly tuned to accommodate the extra material.

6 Recommendation and Outlook

6.1 Hybrid Laser Arc Welding

Hybrid Laser Arc Welding is a process that combines both laser beam and arc welding technologies. Three processes can arise from such combination, depending on the arc used: TIG, plasma arc or MIG. By hybrid process, one means that the laser and the electric arc both act on the welding zone at the same time in a cooperative manner, unlike a dual process where two separate welding technologies act in succession. The process parameters can be tuned so that the overall final product deviates more towards laser welding characteristics or towards arc welding characteristics.

Regarding large gap bridging procedures, hybrid laser arc welding is of special interest due to the necessary introduction of filler wire to fill the gap between the parts. The extra material to melt can render the sole laser process too slow. By introducing an arc in conjunction with the laser beam more heat is available to heat the filler wire, considerably increasing the welding speed. Previous studies (SHI e HILTON, 2005) have achieved welds of the same quality with speeds 2.5 times higher when comparing hybrid laser arc welding with sole laser welding in 8 mm thick steel samples. The same authors have observed increased gap tolerance when utilizing the hybrid welding system; gaps four times as large were bridged when comparing with autogenous laser welding. It was possible to weld parts with gaps of 1.6 mm with correct tuning of parameters, suggesting that real time measurement equipment can enable a system to perform varying gap weld seams.

6.2 Scanning Lasers

The term scanning lasers can have a wide variety of meanings in many fields. In material processing, it refers to enabling rotational motion to the laser head, allowing the laser beam to navigate the weld seam with more complex motion than just a line. This feature allows for a number of advantages, such as gap bridging, increased tolerance for beam position or flexibility in the welding system. Scanning lasers also provide an advantage when breaching gaps in material that have a low viscosity in the liquid phase such as aluminum. Since the beam moves in a very rapid manner it is possible to melt a larger area of the base metal which is required for the gap bridging however for a shorter time, not allowing the material to flow down considerably. Previous studies (FIXEMER, ALBERT, *et al.*, 2015) have shown that it is possible to use scanning lasers in varying gap welds, making online measurement of the distance and adjusting the scanning optics parameters. They obtained success with automatic welding of gaps up to around 0.5 x thickness of the sheets to be welded.

7 Appendix

7.1 Filler Wire Selection

Choosing the correct filler wire is a process that requires some research. The book "The welding of aluminium and its alloys", by Gene Mathers, contains guidance on how to choose the correct filler wire for many cases of base material. The current tables are a part of this guide and can help in a more direct way.

Parent metal	Al-Si Castings	Al-Mg Castings	1XXX	2XXX	3XXX	4XXX	5XXX	6XXX	7XXX
Al-Si Castings	**4XXX**	NR	4XXX	NR	4XXX	4XXX	NR	4XXX	NR
	NS	NR	NS	NR	NS	NS	NR	NS	NR
	NS	NR	NS	NR	NS	NS	NR	NS	NR
Al-Mg Castings	NR	**5XXX**	5XXX	NR	5XXX	NR	5XXX	5XXX	5XXX
	NR	**NS**	NS	NR	3XXX	NR	NS	NS	NS
	NR	**NS**	NS	NR	NS	NR	NS	NS	NS
1XXX	4XXX	5XXX	**4XXX**	NR	4XXX	4XXX	5XXX	4XXX	5XXX
	NS	NS	**1XXX**	NS	3XXX	1XXX	NS	NS	NS
	NS	NS	**NS**	4047	NS	NS	NS	NS	NS
2XXX	NR	NR	NR	**NR**	NR	NR	NR	NR	NR
	NR	NR	NR	**NR**	NR	NR	NR	NR	NR
	NR	NR	4047	**4047**	4047	4047	NR	4047	NR
3XXX	4XXX	5XXX	4XXX	NR	**4XXX**	4XXX	5XXX	5XXX	5XXX
	NS	3XXX	3XXX	NR	**3XXX**	3XXX	NS	NS	NS
	NS	NS	NS	4047	**NS**	NS	NS	NS	NS
4XXX	4XXX	NR	4XXX	NR	4XXX	**4XXX**	NR	5XXX	5XXX
	NS	NR	1XXX	NR	3XXX	**NS**	NR	4XXX	4XXX
	NS	NR	NS	4047	NS	**NS**	NR	NS	NS
5XXX	NR	5XXX	5XXX	NR	5XXX	NR	**5XXX**	5XXX	5XXX
	NR	NS	NS	NR	NS	NR	**NS**	NS	NS
	NR	NS	NS	NR	NS	NR	**NS**	NS	NS
6XXX	4XXX	5XXX	4XXX	NR	5XXX	5XXX	5XXX	**5XXX**	5XXX
	NS	NS	NS	NR	NS	4XXX	NS	**NS**	NS
	NS	NS	NS	4047	NS	NS	NS	**4XXX**	NS
7XXX	NR	5XXX	5XXX	NR	5XXX	5XXX	5XXX	5XXX	**5XXX**
	NR	NS	NS	NR	NS	4XXX	NS	NS	**NS**
	NR	NS	NS	NR	NS	NS	NS	NS	**NS**

Table 16: General guidance on filler metal selection (Mathers, 2002)

Parent metal	1050 1080 1200	2219	3103 3105	5005 5083 5251 5454	6061 6063 6082	7005 7019 7020 7039	8090
8090				5556			**5556**
7039	5556		5556	5356	5556	**5556**	
7019	5356		5356		5356	**5356**	
7020	5183		5183		5183	**5183**	
7005						**5039**	
6061	5356		4043	5356	**5556**		
6063	NS		5356		**5356**		
6082	4043				**5183**		
5454	5356		5356	**5356**			
5251	5356		5356	**5056**			
5083	5356		5356				
5005	5356						
3103	5356	2319	**5356**	5356	5356	5556	5556
3105		NS	**4043**		5056	5356	
	4043	4043					
2219	2319	**2319**					
	4043						
1050	**4043**	2319					
1080	**1050**	4043					
1200	**1080**						

Table 17: Guidance on filler metal selection – dissimilar metal joints for specific alloys

Base material	Highest strength	Best ductility	Salt water corrosion resistance	Least cracking tendency	Best for anodising
1100	4043	1050	1050	4043	1100
2219	2319	2319	2319	2319	2319
3103	4043	1050	1050	4043	1050
5052	5356	5356	5554	5356	5356
5083	5183	5356	5183	5356	5356
5086	5356	5356	5183	5356	5356
5454	5356	5554	5554	5356	5554
5456	5556	5356	5556	5356	5556
6061	5356	5356	4043	4043	5654
6063	5356	5356	4043	4043	6356
6082	4043	4043	4043	4043	4043
7005	5556	5356	5356	5356	5356
7039	5556	5356	5356	5356	5356

Table 18: Filler metal selection to achieve specific properties for the commoner structural alloys

7.2 Weld Seam Fill Factor

Refer to section 3.3 for more information regarding Weld Seam Fill Factor.

Nahtgeometrie	Bereichsgrenzen für W in mm^3/mm	Zielwert für W in mm^3/mm
I-Naht am Stumpfstoß	0,8 – 1,2	0,9
I-Naht am Überlappstoß (Einschweißung)	0 – 1,0	0,9
I-Naht am Überlappstoß (Durchschweißung)	1,0 – 1,6	1,1
Bördelnaht am Überlappstoß	1,0 – 1,5	1,3
Kehlnaht am Überlappstoß	0,7 – 1,0	0,9
Kehlnaht am T-Stoß	1,5 – 2,5	2,0

Figure 33: Values for W depending on joint type and their respective tolerances

7.3 Samples Technical Drawings

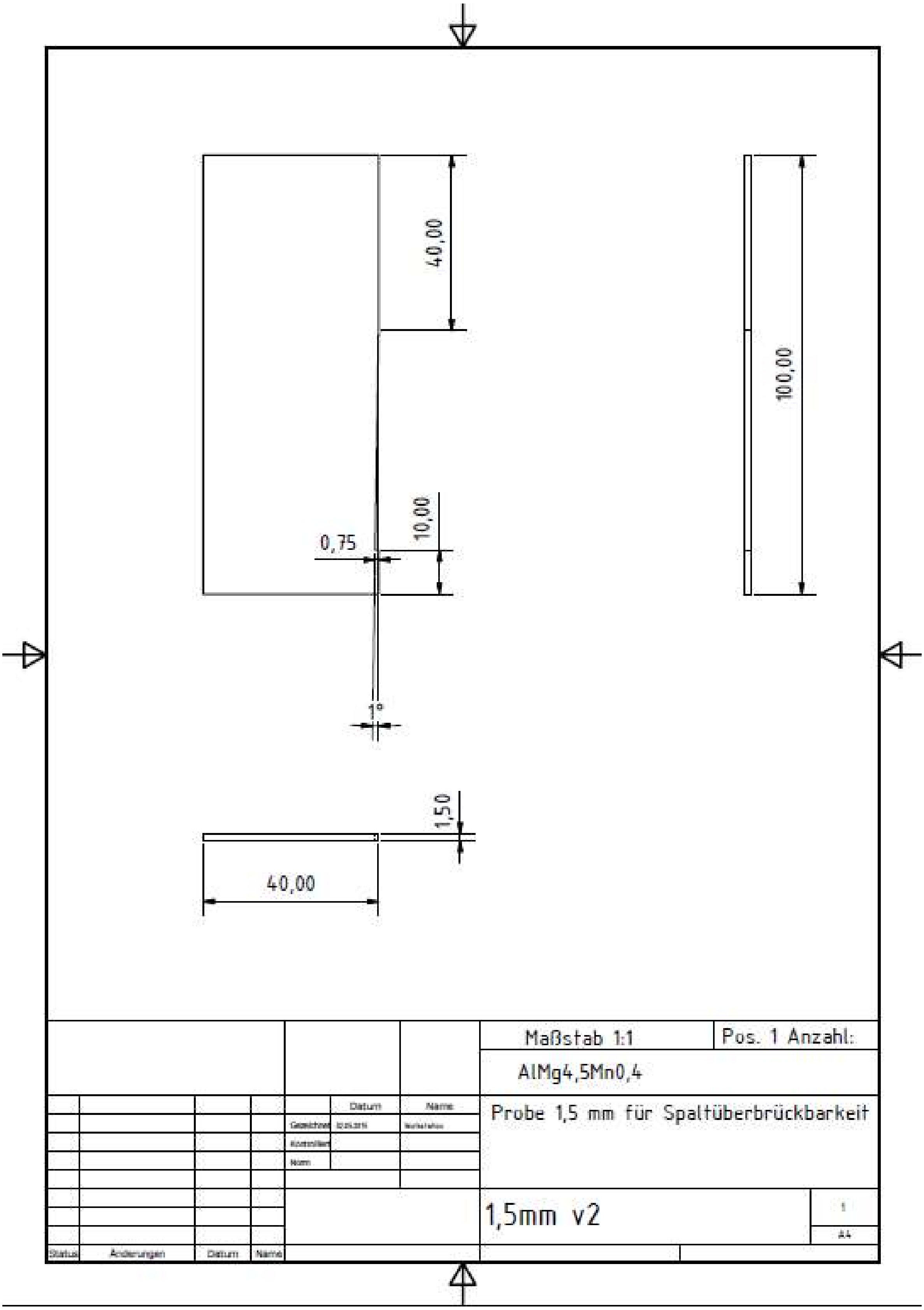

Figure 34: Technical drawing for wrought aluminum samples with 1.5 mm gap

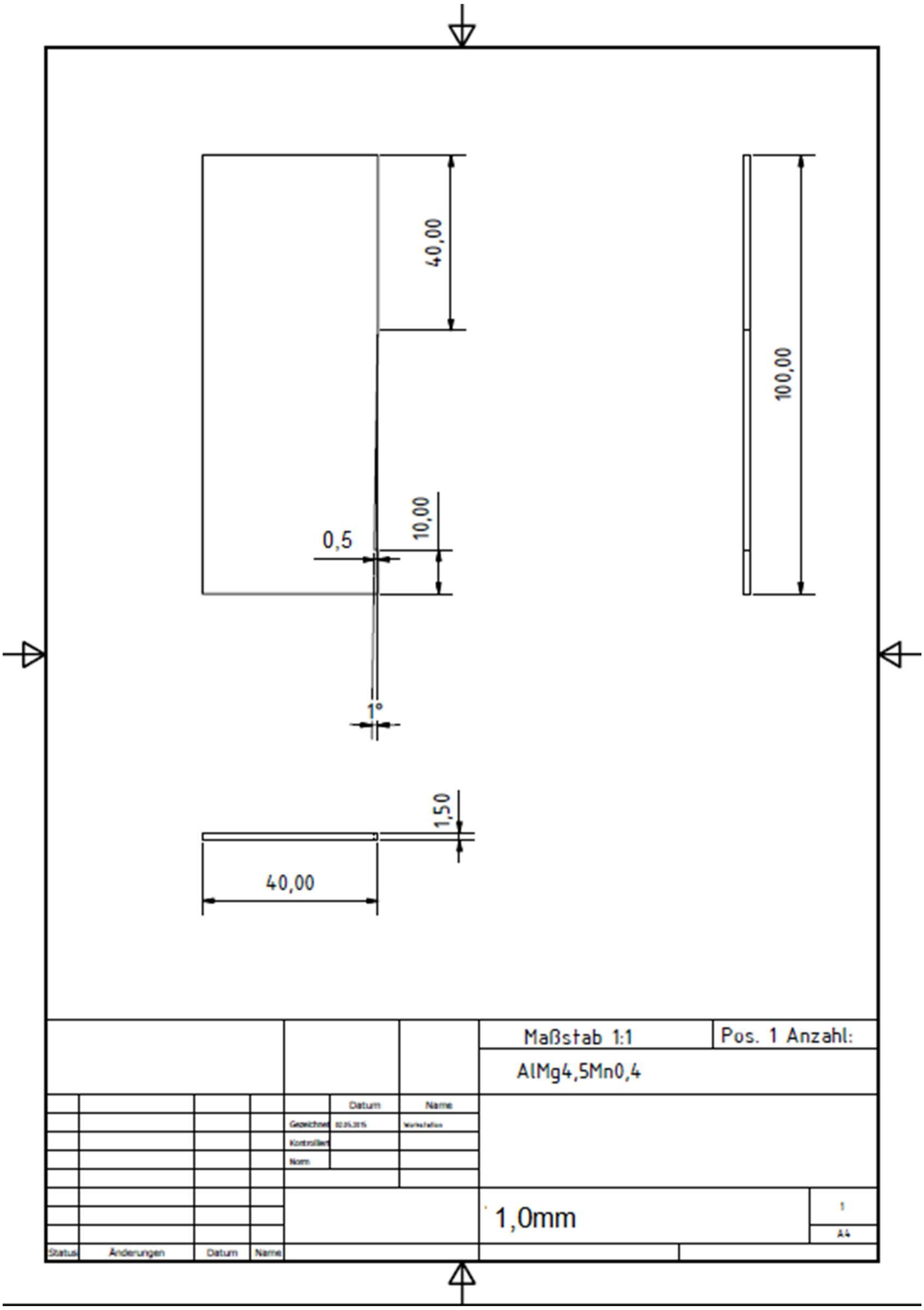

Figure 35: Technical drawing for wrought aluminum samples with 1.0 mm gap

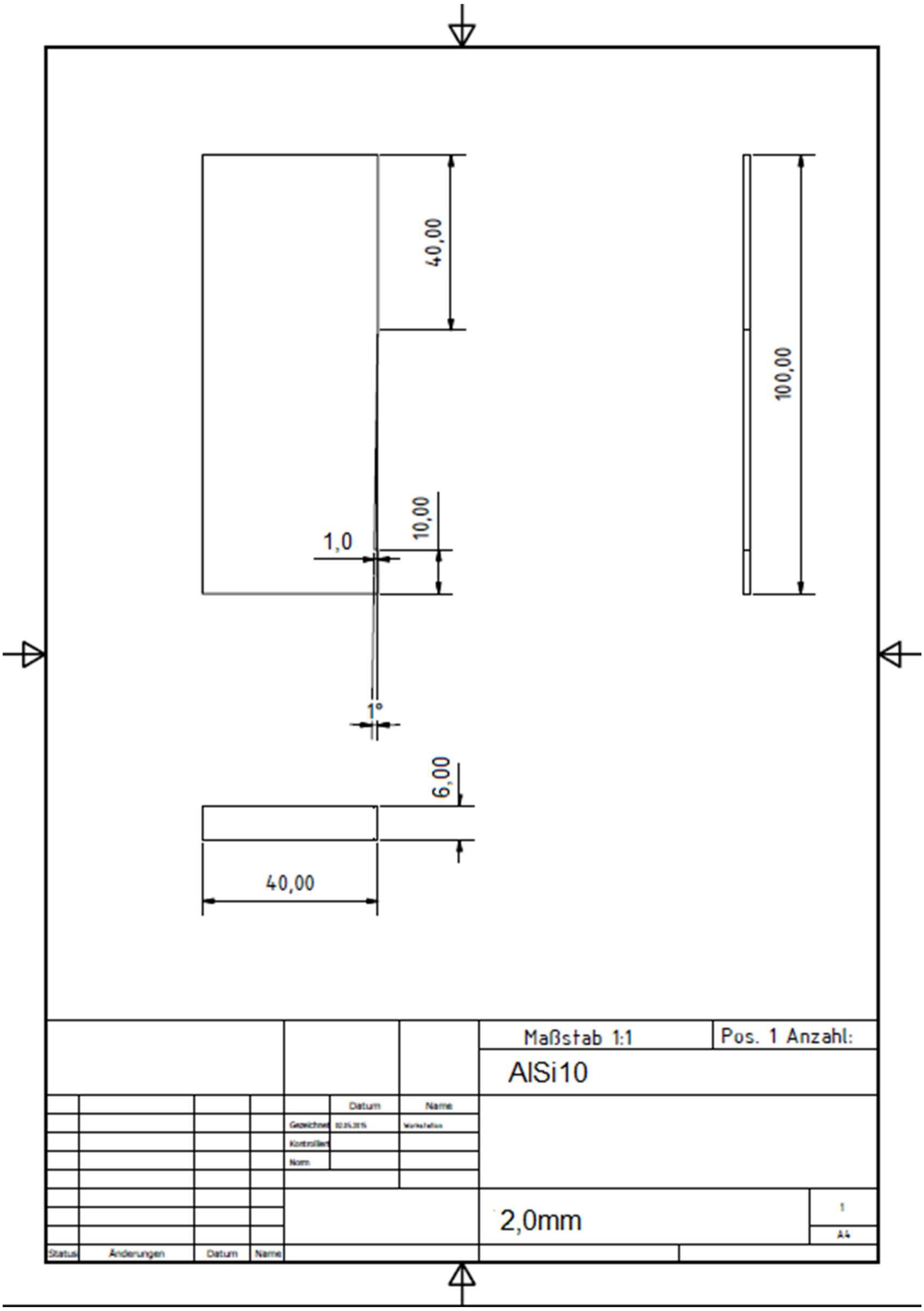

Figure 36: Technical drawing for cast aluminum samples with 2.0 mm gap

7.4 Profile Pictures for Cast Alloys

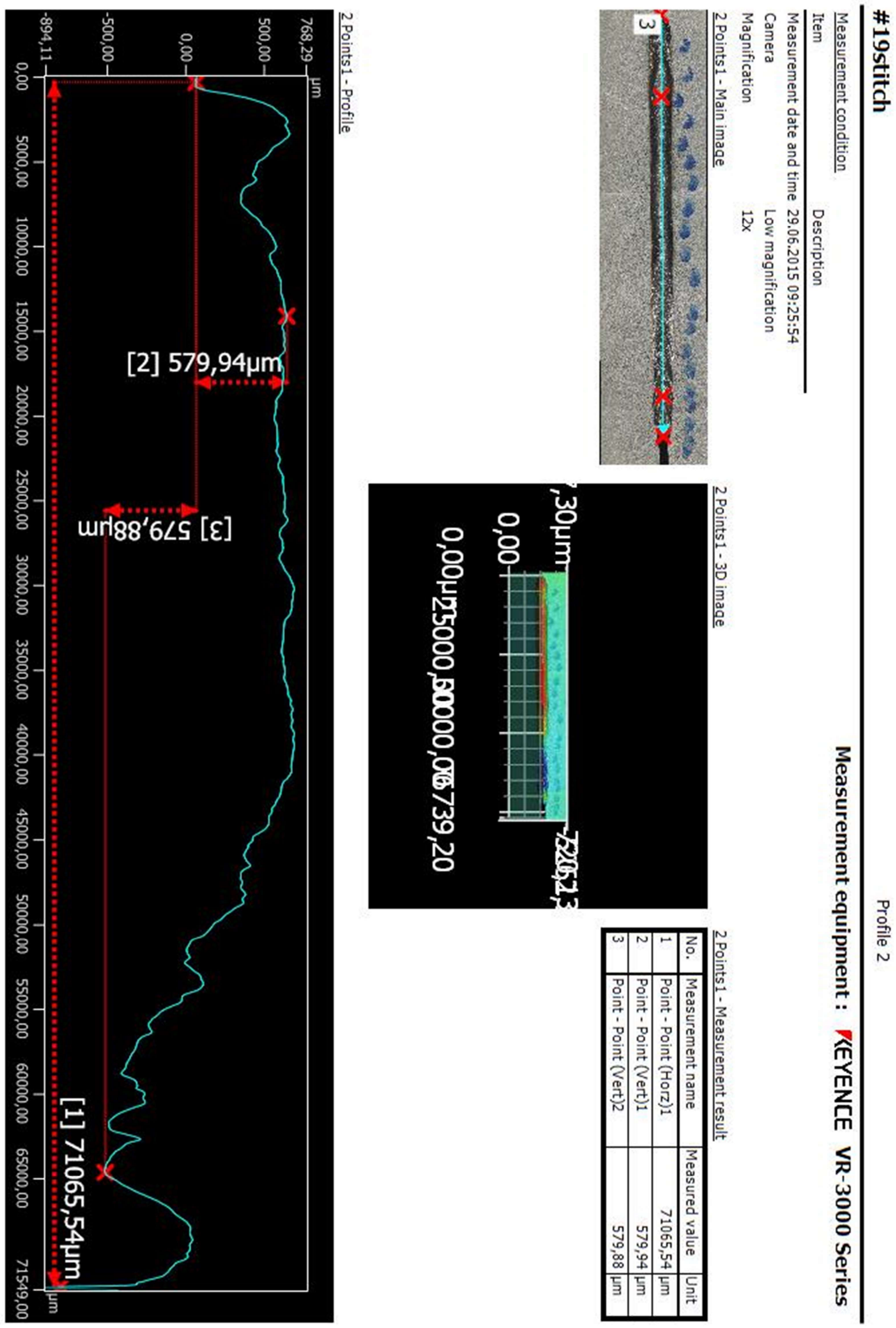

Figure 37: Complete profile picture for #18

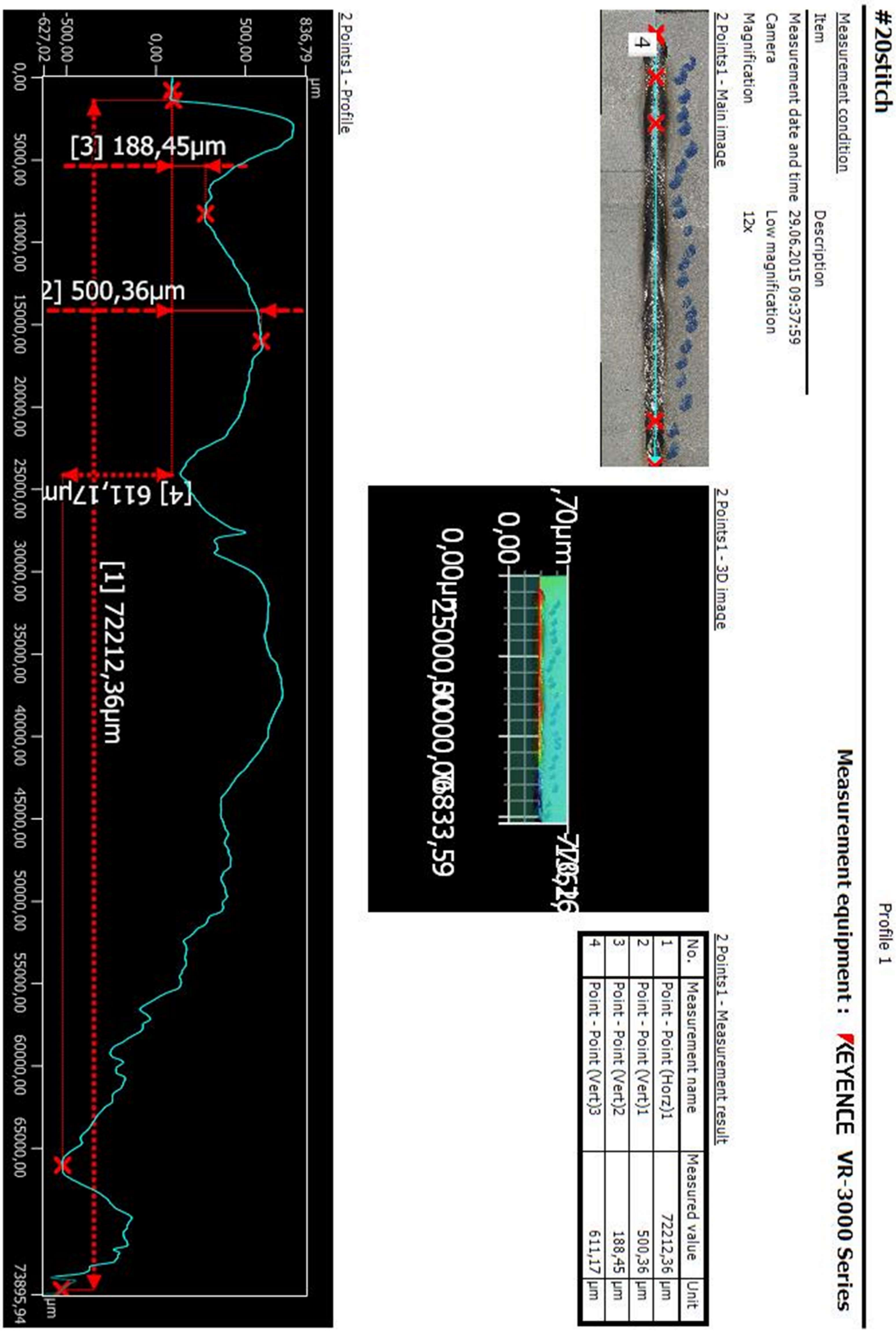

Figure 38: Complete profile picture for #19

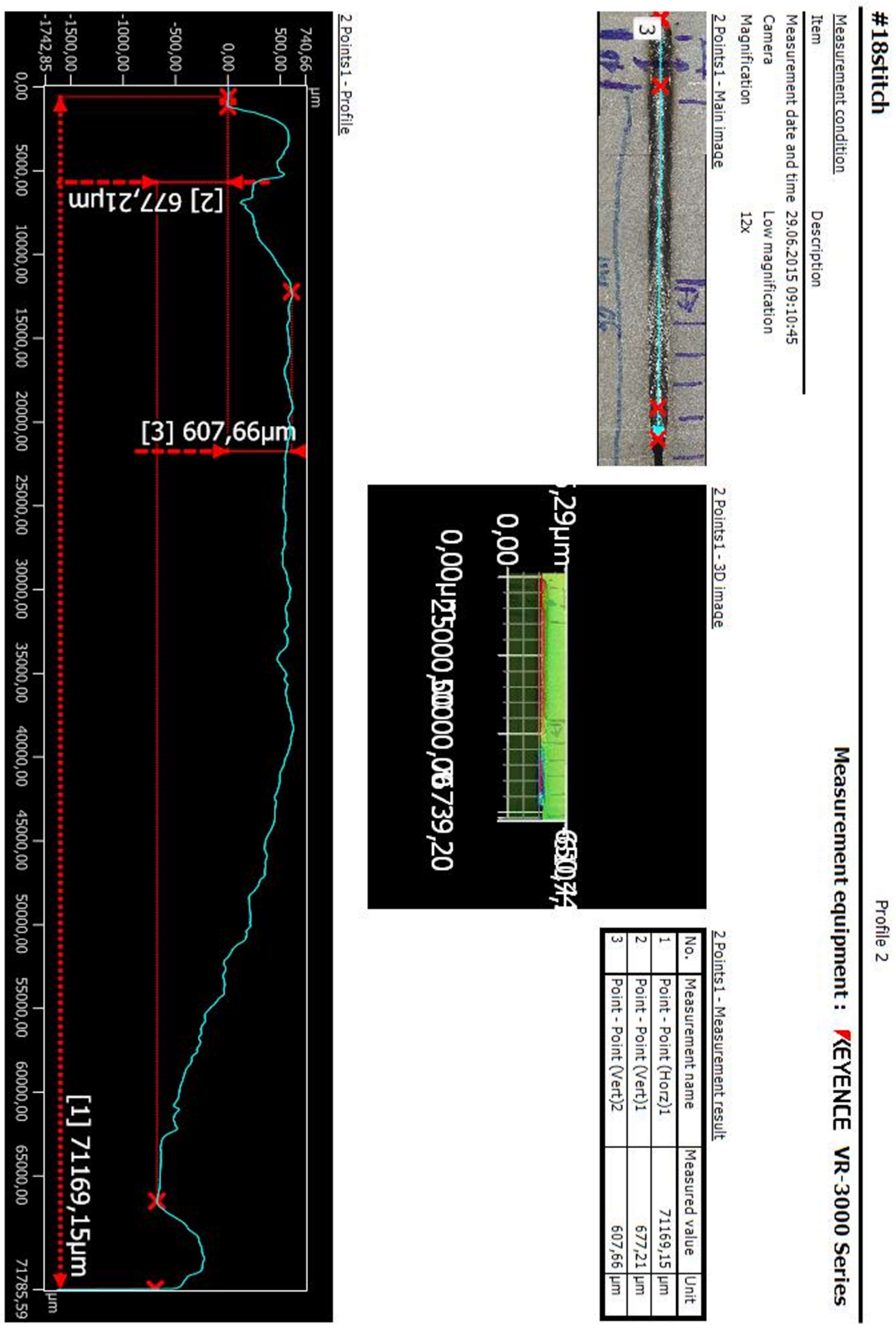

Figure 39: Complete profile picture for #19

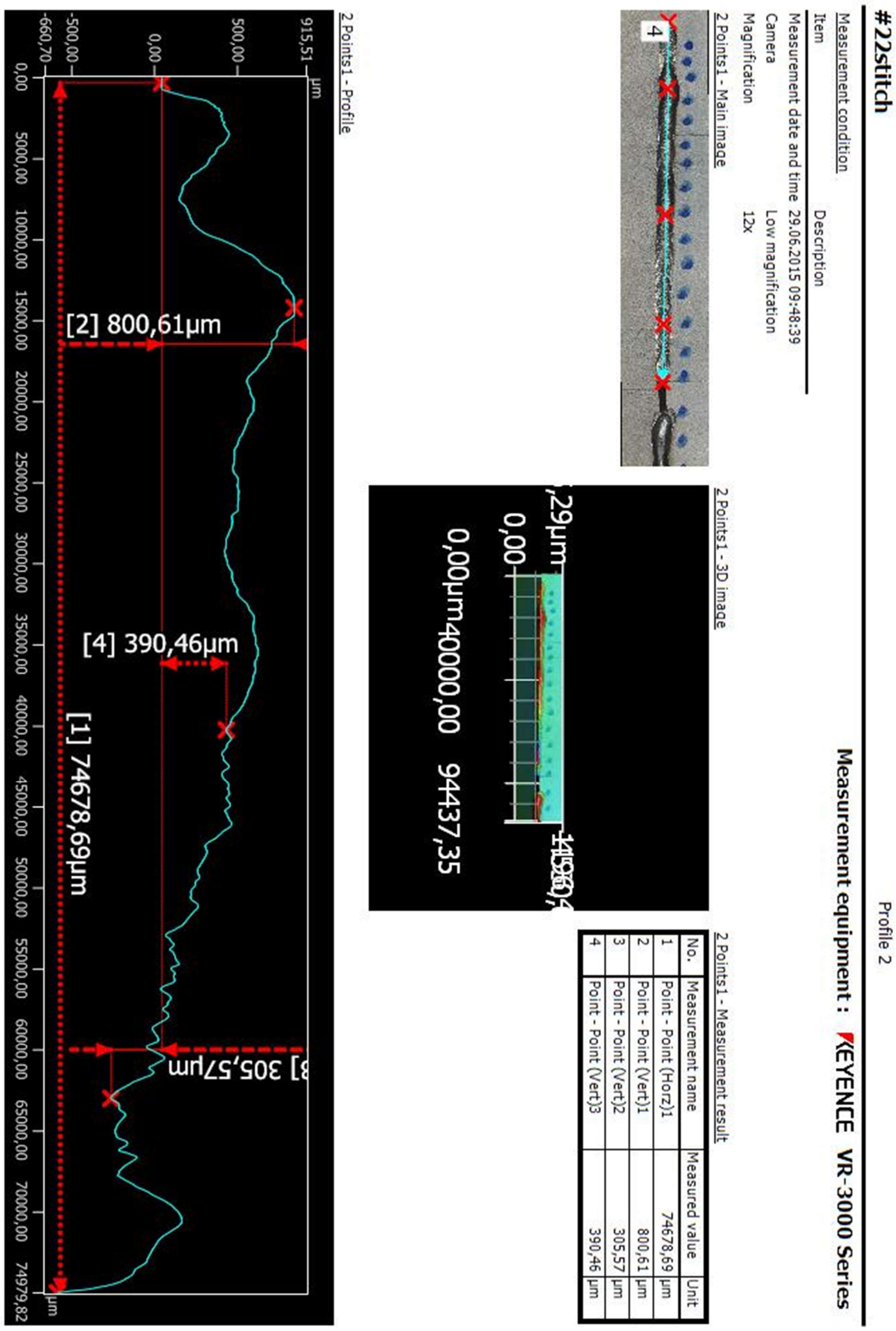

Figure 40: Complete profile picture for #22

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