Bachelor Degree Project

UNIVERSITY
OF SKÖVDE

LASER WELDING FOR BATTERY CELLS OF HYBRID VEHICLES

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Abstract

The report is an overview article, as a result of our investigation at the field of laser welding applied to electromobility cells manufactured in an aluminium housing. This project was proposed by the University of Skövde in collaboration with ASSAR Centre. The key results presented are based on the study of the following parameters: laser type and power, shielding gases, welding modes, patterns and layout. The conclusions of the project define the final selection of each parameter in order to achieve minimum defects and optimal electrical performance by minimizing the contact resistance.

Certification

This thesis has been submitted by Adrián Ros García and Luis Bujalance Silva to the University of Skövde (Sweden) as a requirement for the degree of Bachelor of Science in Mechanical Engineering. The undersigned certifies that all the material in this thesis that is not our own has been properly acknowledged using accepted referencing practices and, further, that the thesis includes no material which we have previously received from any academic credit.

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Table of Contents

List of Figures

List of Tables

1. Introduction

Laser welding processes represent a considerable quality solution for some engineering applications where special requirements appear. This project studies a specific application of this welding technique, in order to find practical and competitive outcomes to be developed in the automobile production in the near future, if not immediately.

This automobile future is compounded by fuel engines vehicles with electromobility cells incorporated into their system. The requirements of the joining process of the electromobility cells and the material features involved makes the laser welding the most acceptable joining process to carry out this solution. Hence, the report focuses mainly on laser welding of the corresponding material, in this case, aluminium.

Other techniques like mechanical fastening provide a reduced effective conducting area between the parts involved in the joint; meanwhile, laser welding processes guarantee a great contact of the aforementioned parts, securing a proper conductivity (Solchenbach, et al., 2014).

1.1. Background

This researching report was proposed in order to enlarge the current knowledge according to laser welding techniques due to the lack of knowledge of the University of Skövde on this field. In addition to optimize the process, improving the weld quality and clarifying the process to be accomplished.

1.2. Problem statement

The University of Skövde is trying to understand this joining process in a deeper way in order to obtain better outcomes in actual performances, in addition to improve the quality of their products and their welding technique. Currently, the University of Skövde in collaboration with ASSAR Centre established a welding method, which outcomes were presented to us at the ASSAR Centre. There, we were told about laser welding advantages among the rest of the welding techniques. The engineer in charge in ASSAR Centre concluded that laser welding performance represents the best current solution to accomplish joints between aluminium electromobility cells, providing an acceptable mechanical response in addition to ensure a proper electrical current flow.

The development of the report is based on an information seeking process, according to the lack of knowledge within this field. As it is mentioned before, a welding method for the electromobility cells joint was developed by a collaboration between the University of Skövde and ASSAR Centre, defining important parameters such as the laser type, laser power and welding mode. These parameters will be checked in our study. Moreover, some improvements will be proposed within the field of electrical flow performance and defects.

1.3. Aims

By developing this project, the principal aim that is sought consists in checking the proposed methodology and improve the quality and electrical performance of the final weld. Furthermore, we aim to complete the missing knowledge with researching studies and to provide real, practical and competitive outcomes to be offered to the stakeholders, as the University of Skövde. The goals to be achieved could be summed up in the next points:

- Clarifying the laser welding processes by researching the different existing techniques.
- Offering a solution to the specific problem presented when welding electromobility cells with aluminium housing.
- Check the process previously developed by a collaboration between the University of Skövde and ASSAR Centre.
- Improving the welding process in order to reduce the defects presented, obtain a high-quality weld and to improve the passage of the electric current through the weld.

1.4. Limitations

Two clear limitations restrict the scope of the project:

- The lack of knowledge in this field. The same reason that makes interesting this project results as a limitation due to the few previous available information.
- The incapability of evidencing our researching in a practical and experimental way. The fact of not having access to laser welding processes in order to contrast the obtained outcomes with theoretical research represents the main limitation when presenting solid results.

1.5. Overview

A brief explanation of each section is going to be given; therefore, the reader can easily follow the flow of the report between one section and another. The project is started with the principles of laser welding where concepts about material properties, types of metals and defects are explained. At Section 3, the main laser welding techniques are explained, it has its own appendix in order to present a wider variety of techniques. Continuing with the next section, the main aluminium features are commented. Furthermore, it has its own appendix where these properties are explained with detail. At Section 5 specific concepts about aluminium laser welding are given focusing on the type of laser, shielding gases, defects, mechanical properties and oscillating patterns. Then, some discussions can be found in Section 6, presenting concepts about laser power, welding layout, motion control and the circularly oscillating pattern. Finally, the conclusions can be found in Section 7, where our selection of the main parameters of the process is proposed. After this section the appendices can be checked, they provide supplementary information of the different sections of the project. Within the appendices, it is notable the sustainability section, where the environmental impact and safety of the welders are discussed.

1.6. Literature review

Useful information needed to develop the current project was found in different sources, among which could be notable the next two:

- Cary, H., 1993. *ASM Handbook, Volume 6, Welding, Brazing and Soldering.* Tenth ed. Geauga Country: ASM International.
- Kautz, D., Milewski, J. & Powers, D., 2007. Laser Beam Welding, Cutting, and Associated Processes. En: A. O'Brien & C. Guzman, edits. *AWS Welding Handbook Volume 3.* Miami: American Welding Society.

Both of them are large handbooks with wide and useful information about general welding processes. These two sources were used at the beginning of our research, in order to create a strong foundation about the welding field. The useful information that was found correspond to the Appendix 2, because it is not related with the aluminium laser welding topic meaning that can not be included as a main section of the report. General aspects of welding are described, as the different techniques or concepts about weldability of the materials and historical background. Furthermore, they contain some detailed information about laser welding techniques and principles being useful for different parts of the project.

Katayama, S., 2013. *Handbook of laser welding technologies.* First ed. Sawston: Woodhead Publishing; contains a large amount of information about the current laser welding technologies. Furthermore, is able to give some predicts about the future of these techniques and the main researching areas for future interests, therefore this source will be used in the development of this report.

1.7. Method

In order to develop the current project, we have established a method to be suitable to the researching process, necessary to find out an adequate solution to the proposed problem. Since the entire project is mostly held on a theoretical basis, the researching process takes almost all the working time and shapes the most important part of the report. According to this criterion, the chosen working method could be divided into the next different steps:

- Background and foundation. The first thing to be accomplished was establishing the basis of welding concept, by defining its history and development, the welding principles and the most important welding techniques. This step means placing our problem in a general area in order to look for its solution.

- Focusing the researching process on the laser welding techniques. Once the problem has been identified and placed in a general field, we have to shorten the limits that contain it, looking for a more specific solution to be adequate to the given problem. This step consists in focusing our researching process in laser welding history, principles, techniques and types of joints that are possible to achieve, and the response of different materials to these joining processes.

- Applying the obtained knowledge to the specific problem of welding electromobility cells with aluminium housing. This is returning to the initial problem, with the necessary knowledge about the laser welding techniques, weldability of the aluminium in these processes and the theoretical requirements to carry out the joint.

- Check the solution given by a collaboration between the University of Skövde and ASSAR Centre and compare it with the outcomes obtained as a result of our researching process.

- Obtaining a solution with minimum defects, maximum quality and optimized electrical performance.

2. Principles of laser welding

In this first section of the report, essential concepts about the influence of the material welded are presented. Including material properties, types of weldable metals and possible appearance of defects.

2.1. Material properties that affect the welding process

The development of this section of the report is based on the studies, experiments and obtained conclusions collected in the paper called *Laser welding; the influence of laser choice and material properties on weld dimensions.* The information about the phenomena exposed in this section is explained in detail within the namesake appendix. As an introduction to the section, it is necessary to describe the two principal cross-sectional shapes presented when laser welding metals, a detailed description of them will be given at Section 3 (Forsman, et al., 2001):

- Conduction welds. These welds adopt a "semi-circular" cross-sectional shape as it is shown in Figure 1

- Keyhole welds. Welds presenting a larger depth/width ratio than conduction welds and adopt a cross-sectional shape as shown in Figure 2.

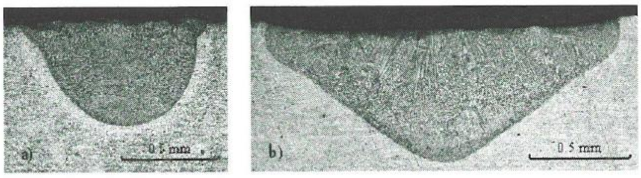

Figure 1. Conduction limited welds cross-section when using a) a CO_2 laser and b) an Nd:YAG laser at a power of 2000 W and a speed of 2m/s in a 2 mm thick Inconel alloy workpiece (Forsman, et al., 2001).

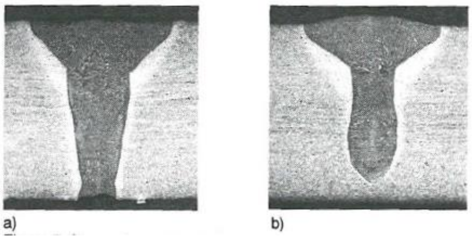

Figure 2. Cross-section of keyhole welds when using a) an Nd:YAG laser and b) a CO_2 laser at a power of 2000 W and a speed of 3m/s in a 2 mm thick Inconel alloy workpiece (Forsman, et al., 2001).

The following concept to introduce in this section is the absorption process. An elementary definition of the absorption process could be: "absorption is 3a process which removes energy from a beam of light traversing the medium" (Liou, 2002). As it is represented with the images above, the Nd:YAG laser creates a larger weld with a bigger penetration in the workpiece. This phenomenon is explained by the greater absorptivity of Nd:YAG laser light than CO_2 laser light and will be explained in more detail by dividing the absorption process in (Forsman, et al., 2001):

- Direct absorption. When the initial laser beam impacts on the melt surface within the keyhole, it is both partially absorbed and reflected meanwhile successive reflections take place.

- Absorption by the vapour in the keyhole for a later re-radiation in all directions, even out of the keyhole.

After accomplishing the same laser welding processes to different types of materials, the referenced paper establishes that the dimensions of the laser welds are affected by different properties of the welded material. Those features are mentioned below (Forsman, et al., 2001):

- Specific heat.
- Density.
- Melting point.
- Electrical conductivity.

Accordingly to these outcomes, the author proposes three affirmations as final conclusions of the current study (Forsman, et al., 2001):

- In laser welding processes with similar parameters and under similar conditions, Nd:YAG laser beam will create a greater amount of melt, and therefore a wider and deeper weld, due to its better absorption.

- The size of the final weld is related to the amount of molten material presented during the welding process, being this amount greater as the electrical conduction decreases.

- The size of the final weld is related to the amount of molten material presented during the welding process, being this amount inversely proportional to density, specific heat (both parameters related to the peak temperature reached during the process) and the melting point temperature of the material to be weld.

2.2. Metals welded

The laser welding process is usually used to weld carbon steels, but can be used to weld different kinds of materials if they are metallurgical compatible, such as stainless steel, nickel base alloys, copper and brass, aluminium, refractory metals and dissimilar metals. This section describes the main materials that can be weld by laser welding. Additional information can be checked in the homonymous appendix (Kautz, et al., 2007).

- **Low carbon steels**. This kind of material is easily weldable with low carbon concentration, specifically lower than 0.25% of carbon content. If this percentage is exceeded, some problems like cracking and brittle welds could appear. In order to avoid this, some pulsating welding can be done by taking some breaks when any welding geometry is done. To improve the characteristics of the weld, some materials as nickel may be added, which increases the toughness of the material (Kautz, et al., 2007).

- **Aluminium and its alloys.** This kind of materials are usually welded with pulsed conduction mode welding. This procedure is used to create some products or packages that need a hermetic seal; in order to achieve this condition, the material should have some residual stress to keep it in constant tension and guaranteeing a correct hermetic seal (Kautz, et al., 2007).

- **Stainless steels.** This group has a huge importance due to one of its properties: low thermal conductivity. This feature allows making an improved weld, by reducing its width and allowing a higher penetration than in carbon steels. This is why the stainless steels are considered appropriate candidates for the laser welding method. Most of stainless steel AISI 3XX series can be easily welded with in general. The AISI 4XX series may develop brittle behaviour and need some kind of post-treatment. Finally, it is remarkable to say that nickel-base and iron-base alloys can also be welded using the laser method (Kautz, et al., 2007).

2.3. Defects and how to avoid them

The defects that are going to be discussed at the following point can be organized at three big groups: **internal defects, external defects** as geometric or appearance issues, and **property defects**. The main defects of the laser beam welding are intern porosity, usually it is formed at deep welding due to the high temperature and power, and hot cracking that can be in a solid state or in a liquid one, this phenomenon appears at the heat affected zone. Continuing with external defects the most remarkable ones are the undercut, underfilling and burn-through. Hereunder an explanation of these defects is going to be given; however, there is a wide variety of welding defects. Hence, if more information is desired check Appendix 3.4 (Katayama, 2013).

The analysis is going to begin with the external defects and the discussion is being started with the **burn-through**. It is a phenomenon produced by the movement of the molten pool. Essentially, a concave surface is created at the top of the weld, and a convex one is created at the bottom surface. When this defect happens, the molten pool is dropped down. This kind of defect happens on thick plates and when deep welding is needed. This defect depends on the surface tension factor of the material that defines the material flows at the welding area (Katayama, 2013).

Some factors can be taken into account if this defect is wanted to be avoided. For instance, using the proper amount of oxygen, likewise working in conditions of low temperatures near the bottom surface and with low oxygen content boosts the formation of this defect. Other actions can be done to avoid it, as optimizing the welding conditions and the use of some tooling like a backing plate (Katayama, 2013).

Finishing with the external defects, the **undercutting** and the **underfilling** are going to be explained. When a trench or trenches are created at the top surface of the welding is called undercutting. This phenomenon occurs at wide and high-pressure welds, this defect is produced by gravity and the way it affects the material distribution over the cooling flow. The way the undercutting presence is dependent on the type of laser beam welding and the type of joint can be reduced by improving the welding conditions. When a concave surface is created at the top the welding is called underfilling, meaning that an incomplete joint penetration has happened. This defect also takes place when a wide weld is being done, and with the butt joint type. It should be mentioned that if this defect appears at a high penetration weld it corresponds to the defect previously explained, burn-through (Katayama, 2013).

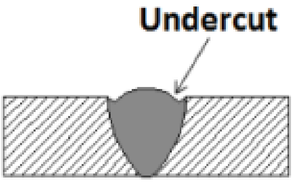

Figure 3. Undercut defect (Katayama, 2013)

Once the external defects have been explained, the discussion can be continued with the most important and common internal defects. The first defect to name is **hot cracking**, and depending on the zone it appears, it can be classified into (Katayama, 2013):

- Solidification cracking: Hot cracking appearing in the weld fusion zone.
- Liquation cracking: Hot cracking appearing in HAZ (heat affected zone).

In aluminium alloys, this type of defect usually takes place within grain boundaries, and it easily occurs when a spot welding or high-speed welding is being developed. This defect has more importance at welding dissimilar materials, in which case it is necessary to control the melting area of the different material (Katayama, 2013).

Another kind of cracking defect is the **cold cracking**, which takes place below 300ºC. Depending on the kind of material in which it is produced and the cause of its appearance, it can be classified into (Katayama, 2013):

Cold Cracking (below 300ºC)		
Name of the defect	**Kind of material**	**Cause of the defect**
Delayed cracking or hydrogen-assisted cracking	·Low-alloyed high tensile strength steels. ·General structural steels.	Provoked by the harmful effects of hydrogen accumulation in highly stress-concentrated zones
Quenching cracking	·Medium carbon steels. ·High carbon steels.	Provoked by the formation of brittle phases of martensite and/or cementite when welding.

Table 1. Cold cracking specifications (Katayama, 2013).

In order to prevent this type of cracking, a heating treatment is required. It can be done before or after the welding operation, being easily repaired in high carbon steels and cast irons. However, high tensile strength steel laser welding may be performed at room temperature, without the necessity of a heating treatment. It can be justified because of the low hydrogen content within the metal composition. (Katayama, 2013).

Finally, the last important defect is **porosity**; this type of defect depends on the welding mode and on the cleanness of the surface. It can happen in the liquid area of the welding nevertheless, it can also affect the solid area. This defect signifies the appearance of air bubbles in the welding area. It is more common at keyhole mode due to the deep penetration of the laser and the high temperatures that are achieved. Generally, it starts at the bottom of the joint generating this kind of bubbles and when the material goes to a solid state these air bubbles generate the porosity of the piece at the weld fusion zone (Katayama, 2013).

If this defect wants to be avoided, hereunder an enumeration of actions can be done: giving some inclination to the laser beam in order avoid direct contact, vary the pulse of the beam, use a twin laser, use the correct shielding gas for the type of joint and material, and making the welding operations in the proper conditions. Focusing on aluminium alloys, some problems can happen related to oxide surfaces and hydrogen. The problematic types of welding in the case of aluminium are the butt-joint and the lap-joint. With these conditions, the bubbles appear in the middle part of the joint and are retained there due to the geometry. If this needs to be prevented the frequency of the pulse waves at the end of the process has to be changed (Katayama, 2013).

2.4. Quality or property defects

The fatigue strengths presented within the joint after a laser welding are commonly greater than the ones appeared when processing other types of welding. This fatigue stress in addition to possible defects appearance such as cracking or underfilling can provoke a serious reduction of the tensile strength of the material. In the homonymous appendix, it is shown a table where the hardness presented in the worked weld is described, as well as the prevention or solution process to improve the joint properties in each case (Katayama, 2013).

3. Laser Welding Techniques

Some concepts that were given previously are going to be developed here below, essentially there exist two main laser welding techniques or modes. This part of the report is focused on explaining these techniques in order to figure out which among them is the most adequate to solve our initial problem.

3.1. Keyhole Welding

This is a deep penetration welding process, where a keyhole is formed by using a high-density energy laser beam (106 W/cm^2 at least). A homogeneous and good-quality weld can be achieved due to the characteristics of the progress and the consequent filling of the gap with the molten metal (Kautz, et al., 2007).

The great magnitude of the energy applied to the workpiece by the high-density energy beam cannot be evacuated by the usual energy transfer mechanisms (conduction, convection and radiation). Therefore, a phenomenon of vaporization of the material in the spot of application happens. This vaporization process creates a pressure gradient, which shapes the keyhole in the workpiece (Katayama, 2013; Kautz, et al., 2007).

Essentially, the pressure difference is what defines the balance of keyhole welding. The pressures involved are surface tension pressure and vapour pressure. The balance between these two pressures is about the closure of the keyhole because the surface pressure tends to close it and the keyhole pressure tends to open it. At this point, the keyhole is a narrow gap formed by "a vapour column surrounded by a thin cylinder of molten metal" (Kautz, et al., 2007), as it is explained in the original reference. As the workpiece is moved to accomplish the weld, the molten metal flows in the opposite direction and solidifies creating the weld as the process advances (Katayama, 2013; Kautz, et al., 2007).

When welding metals by using this process, it is really common that the phenomenon known as plasma suppression appears. This phenomenon consists in the ionization of the gas created when the metal to be welded is heated by the high-density energy beam and consequently, its vaporization occurs. When this vapour is ionized it becomes to plasma, which provokes the attenuation of the laser beam impact and the reduction of the welding depth. The plasma plume can occasionally make the keyhole to collapse. An acceptable solution for this specific problem is to blow gas in the transversal direction of the laser beam, clearing the plasma of the weld. The used shielding gas will depend on the power supplied by the beam, being helium the most flexible gas for high and low-density energy beams. Finally, the speed and volume of gas to be blown will be adjusted to not affect the weld pool and weld quality (Kautz, et al., 2007).

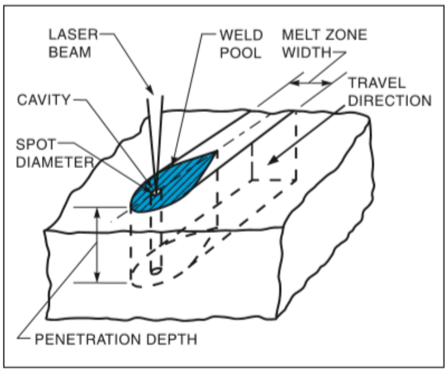

Figure 4. Schematic View of a Keyhole Weld (Kautz, et al., 2007)

3.2. Conduction Welding

Conduction welding mode has many similarities with the keyhole welding; however, the main difference between these two types of laser welding techniques is the depth of the joint. The keyhole welding produces the welded zone along all the joint area, however, the conduction welding occurs when the power of the laser is not enough to accomplish the full depth of the union. This implies that only one segment between the two pieces is welded, meaning that full penetration is not achieved, as it can be observed in Figure 5 (Kautz, et al., 2007).

Essentially, the melting point of the material is reached, but the vaporization temperature is not. Hence, the joining process is completed by heat conduction transfer. Generally, Nd:YAG is the most suitable laser to accomplish this laser welding technique due to its shorter wavelength. In further sections, the types of laser will be explained. (Cao, et al., 2003).

Hereunder some ideas are going to be exposed in order to clarify how the conduction mode and the keyhole mode are produced. Essentially this difference is done with the lenses. When the laser beam is completely focused a high depth is achieved, getting the smallest welding spot possible and the highest temperature of the weld bead. These features belong to the keyhole mode. With a defocused laser beam, the welding spot is increased and the peak temperature decreased, the penetration is reduced too. These features obtained and the weld pool are characteristic of the conduction welding mode (Zhao & Debroy, 2001; Pastor, et al., 1999).

The defocusing explained above is measured with a positive/negative system, which represents the location of the focal point. If it is positive, it means that the focusing point is above the welding surface and if it is negative means that the focusing point is below the surface. If the power is near the limit between keyhole and conduction, the weld geometry does not correspond with any of the two welding modes. This is called transition mode, consequently at this mode, the keyhole could be unstable and even collapse. (Zhao & Debroy, 2001; Pastor, et al., 1999).

Focusing specifically on aluminium alloys, the depth of the weld has a maximum at the stable keyhole, meaning a purely focused laser beam or with small defocusing as ±0.5 has to be used. Working with an unstable keyhole gives also a very deep weld nevertheless, only with negative defocusing, whether positive defocusing is used the depth is being reduced. Therefore, the keyhole is more stable with the focal point above the surface (Pastor, et al., 1999).

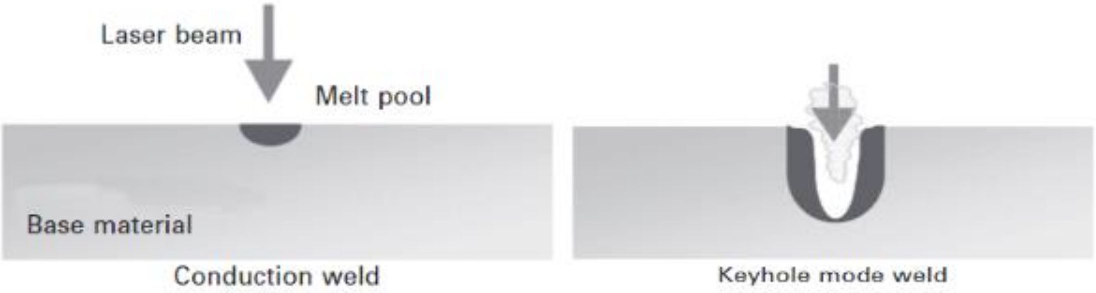

Figure 5. Comparison between keyhole and conduction (Katayama, 2013)

3.3. Additional Welding Techniques.

The main welding modes or techniques have already been explained. More techniques are available that can be used at some specific conditions that have very particular advantages. These welding modes are explained briefly hereunder, whether more knowledge about these techniques is desired the homonymous appendix should be checked.

- Shallow-Penetration Welding. This welding technique is a conduction mode developed in very specific conditions. The power is limited to 1kW and the speed is near to the depth-of-fusion limit (Kautz, et al., 2007).

- Pulsed Laser Beam Welding. This method is very similar to the one explained above. At this variation, the process is developed with a pulsed wave laser, instead of a continuous wave. This method has some advantages, for instance the reduction of the heat affected zone; hence, a higher precision is achieved. In addition, the heat input is also reduced (Kautz, et al., 2007).

- Hybrid Welding. The traditional gas metal arc welding is combined with the laser welding technique in this method. The main heat source is the laser and the gas metal arc is the secondary one. This blend increases the welding speed and stability (Katayama, 2013).

4. Aluminium welding

Once the original problem has been analysed and placed within general limits, it must be studied in more detail. Therefore, the next step consists in going in depth in the aluminium properties, which may facilitate the process union by improving aluminium weldability.

When analysing weldability of metals, a series of properties that affect the aluminium welding process are observed. Among these properties are found thermal conductivity, reflectivity and viscosity. To understand and modify these physical properties is the key to improve aluminium weldability, therefore they will be exposed next.

It was found that aluminium is one of the easiest materials to operate with at any penetration or cut process due to its high ductility. However, it is one of the most difficult ones to weld, specifically with the laser method, due to it has a large electron density that entails a high light reflectivity. Furthermore, aluminium and its alloys present a high thermal conductivity, which permits to easily release the input energy (Huntington & Eagar, 1983).

The main mechanical properties that affect the weldability of the aluminium and its alloys are thermal conductivity, reflectivity and viscosity. These three properties are deeper explained in the homonymous appendix.

5. Laser Welding for Pure Aluminium and Alloys

At this stage of the project, the technologies that can be used for aluminium laser welding are going to be explained, in terms of the type of laser that is used and the selected welding mode. Later on, the shielding gases and their main features will be discussed. Previously at this report, the welding modes have been explained, however, now the discussion is going to be focused in aluminium laser welding. Nevertheless, some concepts are going to appear again. There are two main welding modes, keyhole and conduction mode. The main differences between them are the laser beam energy density and the features of the weld pool generated on the welding process. Mentioning the energy density, it is higher at the keyhole mode allowing a faster process and especially making narrower and deeper weld beads (Katayama, 2013).

Introducing some factors about the keyhole mode is important to mention that this mode is more employed than the conduction mode because it is able to generate the weld with smaller heat affected-zones. This process presents some disadvantages as the instability due to the pressure difference and the porosity. The last defect can be produced due to the intermittent closure produced by the vapour bubbles and gas entrapment. In order to obtain a stable keyhole during the welding process, it is important to select a narrow beam diameter since a turbulent weld pool may provoke a significant formation of cavities (Solchenbach, et al., 2014; Katayama, 2013).

Keyhole mode is a more suitable method to accomplish the electromobility cells joining process due to two main factors presented by aluminium (Solchenbach, et al., 2014):

- Low infrared light absorption.
- High thermal conductivity.

Volatile alloying materials provide the alloys with a lower vaporization temperature and a higher vapour pressure. Therefore, as the percentage of these materials increases at the composition of the alloy, it will be easier to melt because a lower vaporization temperature is achieved. In addition, it will present a more stable keyhole due to the greater vapour pressure. Because of these features, the threshold energy density will be reduced when volatile alloying materials, such as magnesium or zinc appear (Cao, et al., 2003).

Continuing with the conduction mode, the temperature achieved during the process is lower than the achieved with the keyhole mode, hence the conduction mode is a more stable process. The cause of this behaviour is that the energy density of the laser beam is not as high as it is at the keyhole mode. This feature allows to heat the material of the welding zone further than the melting point but not enough to arrive to the evaporation point. This technique is the one utilized with materials that present difficulties with the rest of methods, for instance, aluminium (Katayama, 2013).

The most remarkable difference between both modes consist in the behaviour of the weld pool. When performing a conduction welding process "the weld pool remains unbroken, but opens up to allow the laser beam to enter the melt pool in keyhole welding" (Cao, et al., 2003). This behaviour makes the weld pool remain more stable during conduction mode than in keyhole mode, besides porosity defect is reduced. It has to be mentioned that a third welding mode exists, although it is defined as a transition between one to another, if more information about this mode is desired, Appendix 7 should be checked. (Cao, et al., 2003).

Continuing with the welding modes and the type of laser used, it will be suggested which welding mode should be used with each laser type. There exist two main laser types, CO_2 and Nd:YAG, they were introduced at Section 2.1. Beginning with the CO_2 laser beam, working with high speeds and a low shielding gas flow rate work out well for the conduction mode versus the keyhole mode. Continuing with Nd:YAG, with low processing rates (0.5 m/min) the process works under the keyhole mode however with higher rates (3 m/min) it works under the conduction mode (Katayama, 2013).

An extremely relevant parameter that should be controlled is the wavelength of the laser beam. This parameter affects the absorptivity of the aluminium. Generally, the absorptivity increases as the wavelength is decreased. NdYAG laser has a lower wavelength than the CO_2 laser, the typical values are 1.06µm for the NdYAG and 10.6µm for the CO_2. That is why NdYAG laser is more appropriate to weld aluminium or aluminium alloys (Pastor, et al., 1999).

The process stability becomes greater as the wavelength decreases for two main reasons, both related to its great absorptivity (Cao, et al., 2003):

- The threshold limit for keyhole mode is lower.
- Reduction of harmful plasma effects.

Furthermore, it is said that the most employed lasers are Nd:YAG and CO_2 if the aim is to make a deep weld under the keyhole regime. A third type of laser called HPDL is used mainly on the conduction mode because it has the shortest wavelength among the three of them (Katayama, 2013).

Hereunder it is shown a comparative table between the most used laser types:

CO_2 laser	**Nd:YAG laser**
Higher power output	Shorter wavelength (greater absorptivity)
Greater efficiency	Reduced plasma effects and stable keyhole
Reliability	Fibre optic delivery (welding, cutting and surface treatment processes)
Safety	Easier to control and less maintenance requirements

Table 2. Comparison between CO_2 laser and Nd:YAG laser (Wang, et al., 2016).

Broadly when an Nd:YAG laser is applied greater stability of the keyhole is achieved, entailing a better final weld surface without porosity and uniform ripples. Furthermore, it is possible to perform the welding process at lower speeds due to the better absorptivity and consequent reduction of severe plasma effects (Wang, et al., 2016).

Another important fact is that the shielding gas composition has a huge impact especially at the time when aluminium is being welded with the laser beam method. Albeit laser welding may be carried out without the utilization of shielding gases, their implement leads to the next advantages (Cao, et al., 2003; Katayama, 2013):

- Prevention from oxidation.
- Protection of the lenses.
- Control of several parameters of the process, such as depth of welding and convection within the weld pool.
- Control the vapour produced during the process.
- Prevention of defects such as undercut, porosity and spattering.

The differences between the shielding gases are mainly because of their densities and how parameters as protection and absorption are affected. High-density gases (Ar) have higher protection because they can stay for longer times in the welding zone. However, as higher is the density, the absorptivity coefficient also increases, hence a higher amount of laser radiation is absorbed than with low-density gases (He). Helium can be used as a shielding gas because it has high thermal conductivity; the heat is deviated from the plasma plume, allowing to keep the plasma amount with a small size (Katayama, 2013; Pastor, et al., 1999).

Other gases like nitrogen can reduce the porosity defects on aluminium. The research for the optimum shielding gas mixture is one of the most active fields nowadays. Focusing on CO_2 laser beams, its performance can be improved with the use of helium or helium-argon shielding mixture. It provides a better penetration to the welding process, especially working with aluminium. Going even deeper, it could be established that (Ar) should be used for aluminium alloys that have high reflectivity and conductivity properties, using a high welding speed with a low power. Helium should be used when the process is being developed in the opposite way than with (Ar), this is done by using lower welding speeds and higher powers. On the other hand, Nd:YAG laser beams are shielded by using argon, which is cheaper than helium but absorbs a greater percentage of the laser energy (Cao, et al., 2003; Katayama, 2013).

Using (N_2) as protector gas during CO_2 laser welding helps to reduce porosity due to the formation of AlN cover during the process. Nevertheless, the same gas used in Nd:YAG laser processes does not reduce the appearance of porosity because AlN film formation does not exist. In addition, when the welding process is carried out using (N_2) as shielding gas and a high-density laser (0.4 MW/mm^2) is involved, the resulting weld does not present porosity formation. This is explained by the high temperature achieved in the plume that avoids the introduction of N_2 into the keyhole; therefore, instabilities within it are avoided. Moreover, deep welds free of porosities are performed (Katayama, et al., 2009).

Finishing with this stage of the report, some concepts about laser power and welding speed will be explained. It is reported that when a high welding speed is being used, the width of the weld increases, meanwhile the depth decreases. It has been found a linear relationship between the energy density of the laser beam and the penetration (Katayama, 2013).

5.1. Microstructure

The microstructure of the material involved can suffer significant changes due to the great temperature reached during the laser welding process as a consequence of the high-density energy beam. The higher input energy presented, the lower shear strength achieved in the union due to recrystallization experienced during the process. In order to quantify and analyse these changes, the welded surface is divided into three different zones. From inner to outer zones regarding the weld bead (Solchenbach, et al., 2014; Katayama, 2013):

- Fusion zone (FZ).
- Heat-affected zone (HAZ).
- Base metal (BM).

"The properties of the weld rely mainly on the microstructure of the FZ" (Katayama, 2013); therefore, the study will be mainly focused on the behaviour of this zone. It is remarkable to say the fact that the aluminium alloys involved in our study are A1050/A1100 and A5052, despite the selected reference deals with a range of different alloys that are later named.

After accomplishing a laser welding process within conduction regimen to several aluminium alloys, such as 6082, 7075, 2024 and so on; the outcomes show a dendritic growth within the fusion zone of the different alloys to some extent due to the high solidification rates produced after the process is carried out. This phenomenon provokes a microstructural refinement in this zone, which entails an increase of microhardness on the FZ. Accordingly, it is possible to reach a higher microhardness in the FZ than the one found in the base metal. In order to equalize the properties presented in the different zones of the welded surface, it is convenient to apply a heat treatment to coarse the microstructure within the bead (Kautz, et al., 2007; Katayama, 2013).

5.2. Defects

Aluminium and aluminium alloys laser welding may entail different types of defects that may have already been explained in this report. Among which is worth mentioning the ones appearing below: (Katayama, 2013)

- Loss of alloying elements.
- Porosity.
- Hot cracking.
- Underfilling.

However, only two of them are going to be explained in this section, due to cracking and underfilling have been already explained. Despite this additional information about these two defects can be found in Appendix 7.1.

The most used aluminium alloy series at the laser welding field is the 5XXX series. Its characteristic feature is the magnesium concentration, this one is the main alloying element of the series. This concentration can be affected by the high temperatures producing the vaporization of some percentage of the alloyed magnesium. Loss of magnesium especially at the 5XXX series affects at the strength level, reducing the mechanical properties of the material. For instance, reducing the corrosion resistance, entailing also porosity problems (Katayama, et al., 2009; Zhao & Debroy, 2001; Pastor, et al., 1999).

The strength of this type of alloy increases with the magnesium percentage. The risk of hot cracking is increased too because this defect is directly linked with the magnesium concentration especially if this is an alloy with 1.5% of magnesium or more. The loss can increase significantly the hot cracking susceptibility. Therefore, the composition changes in function with the vaporization flux took into account by the literature reviewed. The evaporation rate has a linear proportion with the laser beam power because it increases with the power used (Zhao & Debroy, 2001; Pastor, et al., 1999).

However, the composition suffers a greater change with lower powers because a small weld pool size appears. This loss means an average value of a 20% strength reduction at the 5XXX series. The magnesium loss is higher with the conduction mode (1%) than with the keyhole mode (0.5%) because it has a smaller weld pool area entailing less temperature diffusion. If the operation is developed with the keyhole mode and it is changed to the conduction mode, signifies the apparition of the unstable keyhole leading to big changes in the magnesium concentration (Zhao & Debroy, 2001; Pastor, et al., 1999).

The temperatures along the weld bead are not uniform; they are higher on the centre and lower on the periphery. This phenomenon produces weld metal flows at the weld pool, these flows are managed by the thermic unbalance and the surface tension. These flows can be up to 1 m/s causing a mixing action between all the weld metal creating turbulences (Zhao & Debroy, 2001).

These flows usually follow the same pattern as the temperature dissipation maps along the surface, confirming that are ruled by the temperature distribution. The vaporization fluxes are ruled by a different phenomenon, instead of the temperature variation, it rules by the pressure gradient. This flux starts at the point where the peak temperature is achieved, essentially almost from the point where the laser beam and the metal interact between them. It can happen at other points due to the thermic diffusion but with much lower rates. These both flows are dependent on the laser beam power and the width of the weld bead (Zhao & Debroy, 2001).
If it is desired to increase the welding speed, and keep the same welding rate or without significant changes, the cross-section of the weld pool has to be reduced. Keeping the same welding rate maintains the same vaporization rate (Zhao & Debroy, 2001).

Continuing with the next defect, porosity significantly deteriorates the mechanical properties of the weld, it can be divided into microporosity and macroporosity. Microporosity is highly related to the hydrogen mixing with the melted metal, keyhole collapse and the turbulence of the weld pool flow. Essentially, it is about the different solubility values of the liquid and solid metal. This phenomenon is not related to the hydrogen that can be in the composition of the alloy. It is referred to the solubility of the hydrogen at the melted metal that could be from the filler material or from the shielding gas. Therefore controlling the amount of hydrogen and maintain it under a specific level (threshold level), could reduce efficiently the porosity of the welded area. In spite of taking this measure into account, the collapse of the keyhole or an excessive turbulent flow at the weld pool could produce porosity (Pastor, et al., 1999; Wang, et al., 2016).

Macroporosity is about the keyhole instability; therefore, some concepts about the defocusing of the laser beam should be mentioned. The porosity has the least percentage of appearance at the conduction mode. Continuing with keyhole mode, it is less with the purely focused beam, and higher with the defocused beam, with very similar values for positive and negative defocusing (Pastor, et al., 1999).

Therefore, it can be established that porosity is formed by an unstable keyhole. If a transition from conduction mode to keyhole mode is done with positive defocusing, a clearly soft transition at the weld pool geometry exists. However, with the negative defocusing it becomes more unstable at the transition stage due to the higher instability of the keyhole and hence increasing macroporosity (Pastor, et al., 1999).

Relating porosity with the welding speed, it can be mentioned that if the velocity of the welding operation is increased a change from keyhole to conduction can be observed. At the transition stage the keyhole becomes unstable, hence highest porosity is obtained. The minimum values are obtained with the conduction mode and with the stable keyhole as it was mentioned before. Moreover, the porosity can be reduced by increasing the cooling rate if changing the welding mode is desired. As a method of prevention, it is significant to say that porosities can be improved by increasing the density of the laser beam and with an incident angle of 50º (Pastor, et al., 1999; Katayama, et al., 2009).

According to the case of laser welding for pure aluminium and alloys, the hydrogen porosity is not the main problem, because filler material is not used and it is more common to have transitions on the welding modes. Furthermore, it is remarkable the fact that porosity in pure aluminium (A1050) is negligible (Katayama, et al., 2009).

5.3. Mechanical Properties

This part of the report is based on different outcomes as a result of experimental investigations with a wide range of aluminium alloys, gathered in the literature consulted.

As a summary of the important information, hereunder is shown the general terms to take into account (Katayama, 2013):

- Higher toughness in FZ than in BM, and therefore a shorter elongation suffered in this zone.
- Laser welds in conduction mode provide a greater fracture load than the ones performed by keyhole mode.
- Mechanical properties have been found to be reduced when the welding process is accomplished with low speeds and laser power.
- Large pores have a great influence on tensile properties, meanwhile smaller pores have negligible influence.
- When the welding process is accomplished with complete control of the parameters, at least "70% of the ultimate tensile strength for the base metal" (Katayama, 2013) is reached within the weld.

Finally, some concepts will be exposed; like that the penetration achieved during the welding process is inversely proportional to the welding speed, which will vary depending on the features of the material to be weld, the beam used in the process and the depth of welding desired. Likewise, high welding speed leads to a fine microstructure within the weld zone, which entails an improvement of the tensile strength of the material, in addition, to reduce the loss of material and alloying material vaporization (Cao, et al., 2003).

5.4. Corrosion

Due to the granular refinement (dendritic growth) within the weld bead, its corrosion resistance is insouciantly improved. Nevertheless, this zone has been found to work as a cathode meanwhile the base metal works as an anode, what may entail intergranular galvanic corrosion with important influence on the heat affected zone (Katayama, 2013).

Post-welding heat treatments represent an appropriate method to reduce this corrosion effect as they reduce the appearing dendrites. In addition to the conventional methods, laser surface melting treatments may be also applied, since they result to be a satisfactory alternative when improving significantly the corrosion resistance in aluminium alloys. There exist two main lasers to carry out this process with (Katayama, 2013):

- Excimer laser: it forms a layer of dissolved constituent particles protecting the alloy (3-10 µm).
- Diode laser: The layer formed is thicker in this case (more than 100 µm).

Despite the fact that these layers created may detach due to the corrosion advance, the literature reviewed stipulate that the future works may look for accomplishing both, union and prevention processes, by using the same laser (Katayama, 2013).

5.5. Oscillating Patterns

As is developed in reference (Wang, et al., 2016), laser beam welding can be improved by performing an oscillating pattern of the given beam while the process is being accomplished. Some of the advantages that this technique offers are shown hereunder (Wang, et al., 2016):

- Reduce temperature gradient as well as the weld hot cracking appearance.
- “Increases the fit-up gap tolerance, and then stabilize the process” (Wang, et al., 2016).
- Present a better bead formation.
- Lead to smooth final surfaces.

There exist three different oscillating patterns to perform: longitudinally oscillation, transversely oscillation and circularly oscillation. (Wang, et al., 2016).

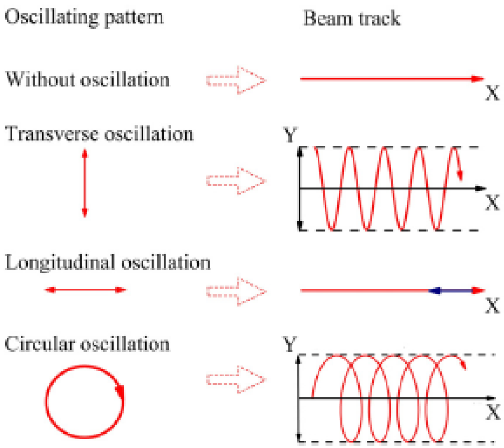

Figure 6. Different welding patterns (Wang, et al., 2016).

6. Discussions

6.1. Aluminium alloys and laser power

There exist two main types of aluminium alloys:

- Non-heat-treatable alloys: A1XXX, A3XXX, A4XXX with silicon as an alloying material, as well as A5XXX. This kind of alloys may be "strengthened by solid solution, cold working, and grain refinement" (Cao, et al., 2003).
- Heat-treatable alloys: A2XXX, A6XXX, A7XXX.

The majority of studies made about aluminium laser welding focus on 5XXX aluminium series, nevertheless, on the presentation that was given to us at the ASSAR Centre, two different kinds of aluminium were welded; one of the 1XXX series that could be A1050 or A1100, and an A5052. Despite they are very similar materials, some differences can be appreciated due to the concentration of aluminium The 1XXX series is considered pure aluminium, due to its 99% aluminium, while the 5XXX series are considered alloys due to the concentration of magnesium. This fact means that both parts will have different absorptivity; the pure aluminium will have less absorptivity due to its higher reflectivity. This difference between the two types of aluminium is lower when working at low powers, however, when working with usual regimes this difference can be up to 20%. Working at high powers the absorptivity of the pure aluminium improves and become even higher than the alloyed. When the keyhole mode is being performed, magnesium vapour is generated and absorbs part of the laser beam energy. This phenomenon reduces the absorptivity of the weld bead. Definitely, the power of the welding process is a parameter to take into account in our decision. An input of 400 W is considered as low power working conditions, 800 W as medium and, finally, input powers larger than 1200 W are established as high power range. In the meeting held at ASSAR Centre, an input power of 1500W was selected as the proposed weld condition, due to they were developing the union with the keyhole mode, hence they need high power welding. (Huntington & Eagar, 1983).

6.2. Welding layout

Regarding the spot size, the energy density will increase as it decreases, albeit the spot may be such reduced that it will be ineffective. As the reference remark: "Migliore recommended that the spot size should be about 30% of the butt-weld width for keyhole welding" (Cao, et al., 2003).

Nevertheless, as it is concluded in the reference (Solchenbach, et al., 2014); a lower contact resistance, as well as a greater shear strength, can be achieved by accomplishing a correct layout of the weld seams. This specific layout is based on "two parallel weld seams with optimized spacing and overlap design" (Solchenbach, et al., 2014).

When performing a single weld seam there exist an increment of the contact resistance when the length of the seam is shorter than its width. In addition to this experimental outcome, it is important to remark the fact that the electrical current does not only flow through the welded interface; however, a significant percentage of it goes through the base metal. Furthermore, when an only one weld seam is accomplished, the electrical current forms a vortex behind it, which provokes a deterioration of the current flow. This effect is shown in Figure 7 (Solchenbach, et al., 2014).

When a second parallel weld seam is performed within the overlap length, this vortex is dissipated to facilitate the current flow through the welded interface. The length of the seams to be accomplished will be half the length of the seam that would be necessary to make the same union with a single seam welding. The comparation between both perfomances can be observed in Figure 7 (Solchenbach, et al., 2014).

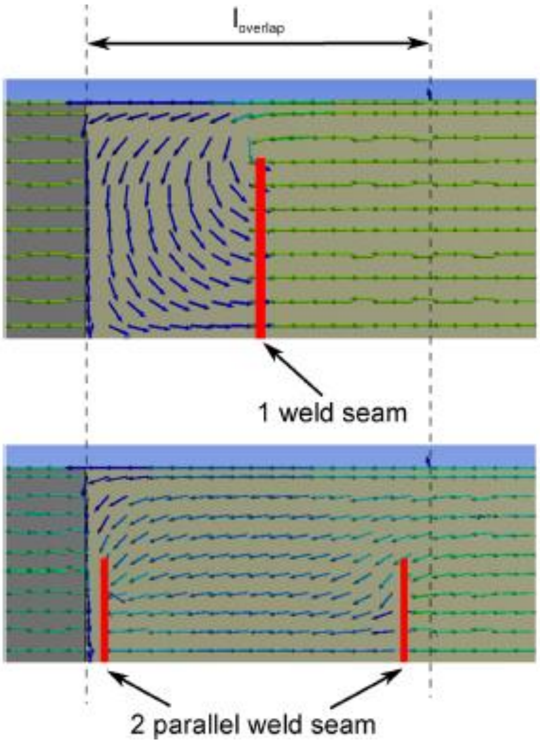

Figure 7. Passage of the electric current when a single seam (upper figure) and two parallel seams (lower figure) are performanced (Solchenbach, et al., 2014).

6.3. Type of laser

Aluminium is a material that presents some difficulties at the time to be welded, being the wavelength a very important parameter. The CO_2 laser is the one that can work with the highest power but also has the largest wavelength compared to the Nd:YAG laser. The numerical values can be observed in Section 5 of this report.

HPDL has the lowest wavelength among the different types of laser. This laser would be the final election if the conduction mode was desired to accomplish the union. By using HPDL, the peak temperature reached during the process will be lower, although the processing time would be increased an important amount of time due to the high thermal conductivity of aluminium. This phenomenon would increase the HAZ of the final weld, due to the features of the welding mode, moreover would negatively affect the process in an economical aspect.

6.4. Motion Control

As laser welding is one of the most complex techniques within this field, in order to achieve a great quality level a high precision is demanded, as well as a high accuracy on the laser positioning. Seam tracking sensors are needed to keep the correct trajectory of the laser beam, nowadays accuracies of 0.2 mm can be reached while working at 250 mm/s with modern techniques (De Graaf, et al., 2010).

Checking one of the last patents about the control of a laser welding machine, a digital pulse control system is used. It consists in automatic motion control of the process by means of numeric control language. This technique counts with five motion axes for the head of the beam, which permits an accurate welding process. Furthermore, it allows the control of the main features of the process, among which may be remarkable the amperage and voltage used by the machine while working. Moreover, this motion control presents available repeatability of the forenamed process by means of the use of digital pulses recorded in a program by a playback device such as a computer, which permits exactly duplicate the given process (J Kerth, 1971).

Accordingly to the seam tracking, it is usually done with different cameras and image-based sensors with a loop control software in order to control the robots. There are two main control mechanism: image-based control and position based control. Accordingly to the position based one, the data is extracted from the camera and it is used on a geometrical model of the surface that wants to be welded. By using this method, it is determined the relative real-time position of the target point in the surface with respect to the position of the sensors, in this case, a camera. Continuing with the image based method, the process that is developed follows the same steps except for the last recognition one, due to the servoing is done directly from the data of the images (De Graaf, et al., 2010).

Comparing the advantages and disadvantages of both of them, the image based architecture is faster, due to it runs one step less (recognition). Therefore, any calculation delay is reduced and the errors committed due to sensor modelling are avoided. The main disadvantage of this method is that controller design becomes a very complex issue to be implemented, since the model starts presenting nonlinearities. However, one advantage that this method presents is huge robustness when talking about the data collection and parameters distortion. Exposing now the position based control, the sensor takes two functions at the same time: the characteristics detection and the identification of the position at every time. This architecture control does not take into consideration parameters like speed. Therefore, a complementary trajectory planner is needed to plan the followed trajectory after specific fixed time intervals by measuring the position. By following this procedure, a constant velocity of the process can be achieved (De Graaf, et al., 2010).

To sum up, the implementation of both control methods at high-speed welding is very difficult and complex. Both techniques use a camera for the measurement of the parameters with a control loop system. Whether delays appear, they should be known and become part of the feedback loop in order to get a correct interpretation and achieve stability. Taking into account these shortcomings, visual servoing technology can be applied to control robotic laser welding (De Graaf, et al., 2010).

6.5. Circularly Oscillating Pattern

This part of the report is dedicated to explain the advantage of circularly oscillating pattern in comparison with the other two existing patterns. The first remarkable advantage regards the defects formation when performing these different patterns. Both longitudinally and transversely oscillating welding present spattered final surfaces, in addition to undercut defect, which can be reduced by using circularly oscillating welding (Wang, et al., 2016).

During oscillating welding, the keyhole suffers a periodic cycle of expansion and shrinkage. When the keyhole is expanding, part of the molten metal within the molten pool jumps out of it and spatters the surrounding surface. After the ejection occurs, the keyhole experiences a shrinkage process entailing a decrement of the molten metal level within the weld pool. These effects are increased by the reversal movement of transversely and longitudinally oscillating patterns, meanwhile, circularly oscillating movement mitigates this spattering cyclic process by stabilizing the keyhole (Wang, et al., 2016).

The second advantage of the circularly oscillating pattern is the microstructure achieved after its performance, which improves some mechanical properties of the aluminium as it is explained next. Axial grains in the columnar structure are formed when performing welding processes without oscillation beam. Nevertheless, the performance of circularly oscillating welding entails the formation of equiaxed structure within the fusion zone of the weld due to the decrease of temperature gradient. This structure appears in 52% of the final weld profile, which is the greatest percentage achieved among the different oscillating welding processes, as circularly oscillating welding present the greater fusion zone and heat-affected zone (Wang, et al., 2016).

The appearance of equiaxed grains structure entails an increment of strain which may reach a 38% higher than an aluminium performance without beam oscillation welding. As a summary, “the circularly oscillating weld has the finest and the most dispersive dendrites meaning that it has the highest microhardness according to Hall-Petch relationship” (Wang, et al., 2016).

On the other hand, the oscillating processes do not affect the tensile strength of the aluminium; however, they increase significantly the strain. In the case of circularly oscillating welding, the strain is increased 38% in comparison to laser welding without beam oscillation (Wang, et al., 2016).

Finally, the circularly oscillating pattern offers the most stable keyhole, becoming the most reliable pattern to be used during penetration welding processes. The calculation developed at the reference shows that “the beam spot moving velocity and the energy absorbed by laser keyhole of circular oscillation almost keep stable during welding” (Wang, et al., 2016), which entails the most stable process achieved among the different oscillating welding processes with the smoothest weld surface by avoiding spattering of molten metal and undercut defects (Wang, et al., 2016).

7. Conclusions

- **Welding mode.** The selected welding mode is keyhole due to the high reflectivity and thermal conductivity of the aluminium. A smaller wavelength is required to achieve a higher penetration, which will permit short processing times, and in turn, better control of the molten material within the weldpool and a finer weld seam will be generated.

- **Power.** As the selected welding mode is keyhole, high power is required, which was established as higher than 1200 W. Therefore, the 1500 W power used in the proposed solution was the correct choice.

- **Laser type.** Nd:YAG is the chosen one due to its lower wavelength compared to CO_2 laser. Albeit the HPDL has an even lower wavelength, it would be more accurate for the conduction welding mode, being in this case, Nd:YAG the best available option.

- **Shielding Gas.** An argon and helium mixture is selected. On one hand, the helium is able to keep the plasma plume on a reduced spot size, with this selection the HAZ is reduced benefiting the state of the battery cells. On the other hand, argon is selected because it is able to increase the protection of the welding area and reduces the cost of the shielding gas.

- **Layout.** As a conclusion to be taken into account regarding to the weld design, the best electrical performance is achieved when carrying out two parallel weld seams within the overlap length. These seams should be as separated as possible by performing the weld seams nearby both extremes of the overlap. As it is explained in the first reference, “the contact resistance decreased linearly with increasing seam distance, independent from the overlap length” (Solchenbach, et al., 2014). Two parallel welding beads correspond to the chosen layout.

- **Oscillating pattern.** Circularly oscillating pattern is the chosen one, due to three main reasons. As it has been previously explained, by carrying out this technique, defects like the underfilling, undercut and spattering are reduced. Moreover, it improves the strain, which is increased a 38% compared to an average union due to the grain formation taking place after applying this technique. Furthermore, this pattern provides the most stable keyhole, which is the selected welding mode.

With the current researching work, the initial aim of verifying the previous method and improving its electrical flow is completed. A theoretical study of laser welding in aluminium electromobility cells has been accomplished, taking into account important parameters that define the final state of the joint. In this final section of the report, these parameters are delimitated in order to achieve an outstanding result. For future development, it is required a practical test of the method here exposed with aim of proving the high-quality performance that is searched for.

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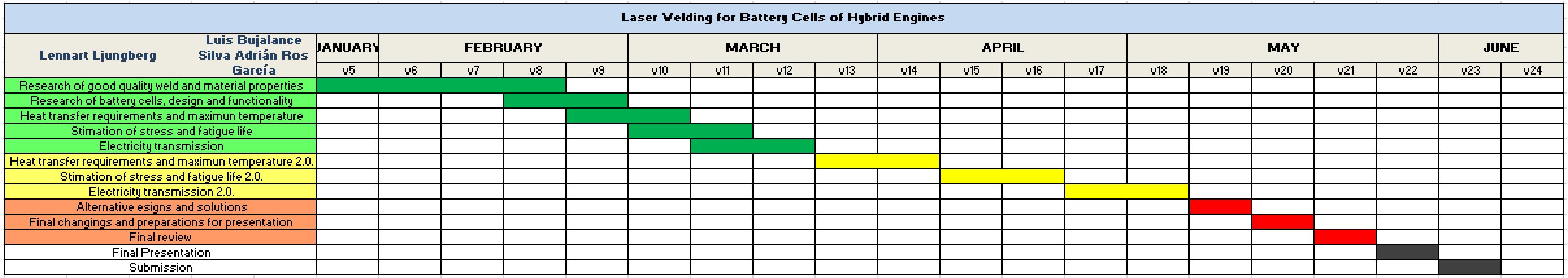
Appendices

Appendix 1. Work Breakdown and Time Plan

Appendix 1.1. GANT Diagram

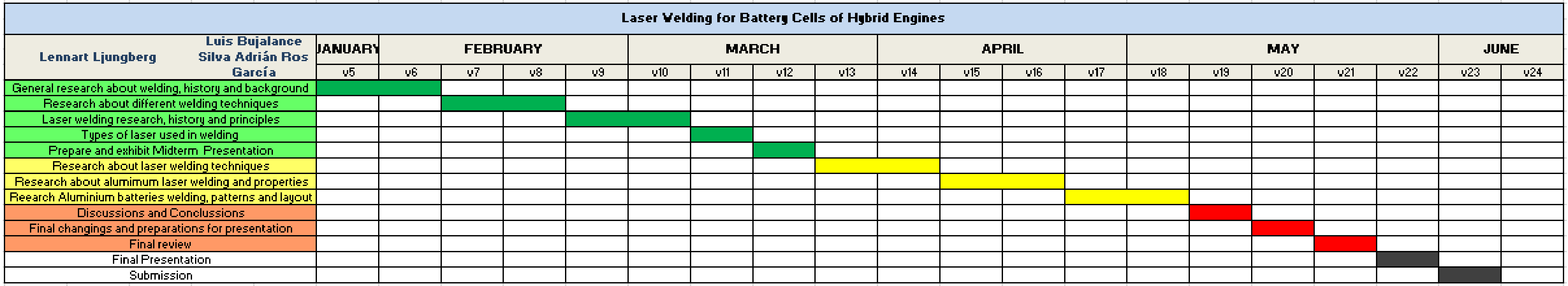
Hereunder the different versions of the Gantt chart of our project can be observed. It has suffered some changes due to the redirection of the project recommended by our supervisor and our own judgement. At first instance, it was a general research project about the laser welding field in order to accomplish an electromobility cells joint. However, we took the decision to focus our research at the main features of this technique, therefore we could check if the elections made by the University of Skövde about specific parameters were the most appropriated ones. In addition, some improvements in the electrical flow field are proposed in order to improve their election. This methodology is represented in the last version of the Gantt chart.



Laser Welding for Battery Cells of Hybrid Engines

Lennart Ljungberg Luis Bujalance Silva Adrián Ros García	JANUARY	FEBRUARY				MARCH				APRIL				MAY					JUNE	
	v5	v6	v7	v8	v9	v10	v11	v12	v13	v14	v15	v16	v17	v18	v19	v20	v21	v22	v23	v24
Research of good quality weld and material properties	🟩	🟩	🟩	🟩																
Research of battery cells, design and functionality				🟩	🟩															
Heat transfer requirements and maximun temperature					🟩	🟩														
Stimation of stress and fatigue life						🟩	🟩													
Electricity transmission							🟩	🟩												
Heat transfer requirements and maximun temperature 2.0.									🟨	🟨										
Stimation of stress and fatigue life 2.0.											🟨	🟨								
Electricity transmission 2.0.													🟨	🟨						
Alternative esigns and solutions															🟥					
Final changings and preparations for presentation																🟥				
Final review																	🟥			
Final Presentation																		⬛		
Submission																			⬛	

Figure 8. *First version of the Gantt chart.*



Laser Welding for Battery Cells of Hybrid Engines

Lennart Ljungberg Luis Bujalance Silva Adrián Ros García	JANUARY	FEBRUARY				MARCH				APRIL				MAY					JUNE	
	v5	v6	v7	v8	v9	v10	v11	v12	v13	v14	v15	v16	v17	v18	v19	v20	v21	v22	v23	v24
General research about welding, history and background	🟩	🟩																		
Research about different welding techniques			🟩	🟩																
Laser welding research, history and principles					🟩	🟩														
Types of laser used in welding							🟩													
Prepare and exhibit Midterm Presentation								🟩												
Research about laser welding techniques									🟨	🟨										
Research about alumimum laser welding and properties											🟨	🟨								
Reearch Aluminium batteries welding, patterns and layout													🟨	🟨						
Discussions and Conclussions															🟥					
Final changings and preparations for presentation																🟥				
Final review																	🟥			
Final Presentation																		⬛		
Submission																			⬛	

Figure 9. *Last version of the Gantt chart.*

Appendix 2. Welding Background

“Welding is a materials joining process in which two or more parts are coalesced at their contacting surfaces by a suitable application of heat and/or pressure” (Groover, 2010). The use of heat and pressure can be done by using only one of them or by using both at the same time. *“*In some welding processes a filler material is added to facilitate coalescence*”* (Groover, 2010). Welding is usually related to the joining of metallic pieces but also can be used with plastic materials. The final product is only one entity called weldment, and the joints of this entity could have a higher strength than the original materials if some filet metals are used and the correct welding method is accomplished. “Welding is usually the most economical way to join components in terms of material usage and fabrication costs. Alternative mechanical methods of assembly require more complex shape alterations*”* (Groover, 2010), some examples that could be mentioned are drilling, rivets or screws. The main advantage of welding compared to the mechanical joints is the placement for the operation, this means that the welding process can be done at the workplace instead of being previously manufactured at a factory, because of the majority of welding processes can be done manually with portable equipment. Consecutively, it should be exposed that this kind of processes require a huge amount of energy making it threatening to the worker therefore, the security instructions must be followed. It provides a permanent joint, hence if disassembly is required this method should not be used (Groover, 2010).

Finally, it is remarkable to say that the welding processes can be applied to metals or thermoplastics. Welding can only be applied to this type of polymers because if not the material will get burnt instead of melt (World Health Organization, 1989).

This appendix is divided into different subparts containing the basic knowledge about the generic welding concept. Furthermore, an introduction to laser welding is included by a brief explanation of its history. Within this content it is possible to distinguish the next main points:

- Welding history.
- Welding principles.
- Welding techniques.
- Laser welding history.

Appendix 2.1. Welding History

Starting with the first signs of welding metals date back to 5000 years ago, when the Aegean Bronze Age began. The welding works found belonging to this time were carried out by simple heating and hammering, a process which is followed nowadays in some procedures of welding metals. It is not until the late nineteenth century that modern welding technology is developed, including oxy-fuel welding. This welding technique was rapidly developed during the early years of the twentieth century, presenting impressive quality advances during the First World War (World Health Organization, 1989).

Although the electric arc phenomenon was discovered in 1802 by Humphrey Davy, it is not until 1882 that Nikolai Bernardos used this method to melt ferrous metals by the use of carbon electrodes. Finally, Charles Coffin utilized metal electrodes in 1892. The slow early development of this technique is due to appearing nitrogen embrittlement problems, which were significantly reduced when asbestos strings started to be used as electrodes. According to flux coating, a lot of different materials were probed to achieve a better weld quality by its coalescence, which was obtained when minerals were added to act gases and slag formers. Among these improved outcomes highlight the ones derived by the utilization of water-glass (sodium and potassium silicates). This welding process where the use of protecting material was involved, became into manual metal arc welding (MMA) during the 1930s decade, meanwhile asbestos kept being used until 1950s. Referring to electrical resistance welding, it was also developed in the nineteenth century and presented better results against embrittlement than arc welding processes (World Health Organization, 1989).

After the increasing application of welding joints during the First World War in order to produce the demanded armament, resistant welding techniques experienced an increment of utilization due to its implementation in vehicles industry, for lately being adopted in different manufacturing fields. The Second World War implied a notable growth and outspread application of welding techniques due to its implication in ships and tanks building and early problems with hydrogen embrittlement were overcome when basic low-hydrogen MMA electrodes were developed in early the 1940s (World Health Organization, 1989).

In addition to this welding technique, some other welding techniques were developed in the latest years of the war, such as submerged arc welding and tungsten inert gas (TIG) welding, introduced by Russell Meredith in late 1930s. TIG was used to replace rivets in aluminium and magnesium joins using the inert gas helium and a tungsten electrode. TIG turned out to be the first successful gas-shield welding technique. In the late 1960s, a variant of TIG welding called plasma arc welding was developed, which can be used for both cutting and welding processes (World Health Organization, 1989; Cary, 1993)

After the Second World War, welding became the principal industrial method for metals union, which resulted in a rapid development in welding technology. Metal inert gas (MIG) welding was used for the first time in 1948, which represents the first gas-shielded welding process with a consumable metal electrode. In order to overcome the problems presented when using cheap shield gases such as carbon dioxide, new welding wires appeared in the early 1950s, carrying antioxidants to protect the weld. This implementation made possible CO_2 shielding with reduced porosity problem of this welding technique, which became to be known as metal active gas (MAG) welding (World Health Organization, 1989).

In the late 1950s was developed a semi-automatic welding technique by using tubular electrodes that totally replaced the previous hand-held tubular electrodes. Tubular electrodes with gas-forming compounds that allowed a "self-shielded" flux-cored welding was developed at this time as well, becoming very popular since the 1960s and beyond due to their capacity of controlling the oxidation and alloying of the weld metal (World Health Organization, 1989).

Recent developments have made possible the automation of the welding process, where different parameters such as the involved voltage can be computer-programmed to increase the accuracy of this technology. Since the 1970s laser welding has experienced a widespread implementation, hence the aim of this report is to go in depth in this field and try to figure out if this technique turns out to be adequate for the matter that concerns us (World Health Organization, 1989).

Finishing with the historical background, some concepts about the evolution of the use of the thermoplastic will be explained. After World War II, thermoplastic importance raised especially at the automobile and industrial field. The best example of this evolution is the plastic intake manifolds of the engines that were manufactured with thermoplastic with the lost core moulding technique. This process was interesting because for opening the possibility of substituting materials like steel or aluminium with plastic. However, this manufacturing process is expensive because the manifold was produced like a single piece (Grewell & Benatar, 2007).

The next step of the evolution of this project was to produce the manifold in two parts and unite them using vibration welding. The main advantage of this development was that bigger manifolds could be manufactured, opening the way for bigger engines, increasing the power of the developed vehicles and industrial processes (Grewell & Benatar, 2007).

Appendix 2.2. Welding Principles

Once the background and the historical introduction has been made, the main principles that define the weldability of a material can be explained. These principles depend on the process selected to carry out the welding. Due to the chemical transformations that take place during welding, some materials can be welded by using specific processes.

In the next section of this report, the types of welding are going to be explained and analysed in order to give a wider explanation of the selection of materials and what is happening during the process. Hereafter, some concepts about the weldability of steels and plastics will be exposed.

First of all, to talk about weldability, the structure of a weld should be understood. The simplest case is chosen and shown in Figure 7, a single-pass weldment. Two weld regions can be easily recognized, the fusion zone and the heat-affected zone (HAZ). At the first region, the material changed its state of matter from solid to liquid and then again another change of state to solid takes place. The final weld depends on several factors such as the peak temperature or the chemical composition, in addition to the consumables and the cooling. These two last factors also define the impurities, the homogeneity and continuity of the weld. Continuing with the heated zone, this is the region where higher temperatures happen. However, they are lower than the melting temperature, which does not mean that the temperature achieved will not be at the austenitic temperature range. If this happens, the precipitated austenite grains could dissolve, and consequently, the boundaries of the grain will unpin and the grain will increase its size forming another type of grain (Liu & Indacochea, 1990).

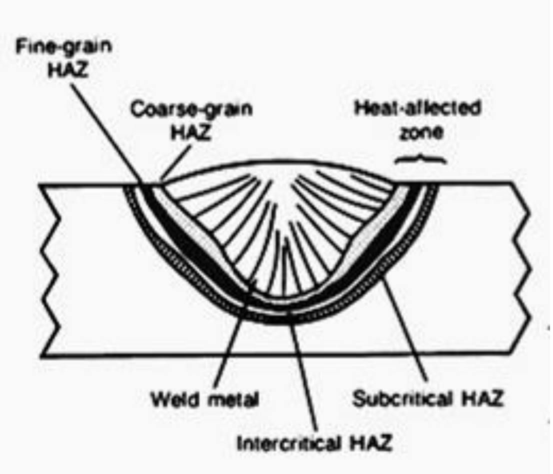


Figure 10. Structure of a Weld (Liu & Indacochea, 1990).

The next stage treats some factors that affect weldability. This analysis is going to be started with the hardenability of the material. It is known that this parameter is generally used to analyse the microstructure of a steel-alloy by means of the distribution, size and shape of the grains that define the hardenability of the material. This method may also be used to select the material and welding method to avoid excessive hardening and cracking at the heat affected zone, due to very high temperatures (Liu & Indacochea, 1990).

Steels with high hardness usually have a big concentration of martensite, which is very sensitive to high temperatures below the melting one and commonly produce cracking at the heat affected zone. Some empirical expressions were obtained in order to determine the weldability of the steel, correlated with the cracking susceptibility. Essentially, the main use of this application is to establish if a heat treatment is needed in order to restore the cracked area. Another factor could be the chemical composition effect, this is usually studied using CCT diagram that is formed by two types of data: the percentage of transformation and the cooling curves The chemical stability regions, in correlation with the thermal conditions experienced by the weld, are obtained with this data. Essentially, the conclusion drawn from these types of graphics is that the hardenability elements like manganese, molybdenum and especially carbon in steels, affect to the austenite decomposition. Hence these diagrams are changed. These elements refine the grain of the microstructure, reducing the hardness of the steel, therefore, the also reduce the cracking risk at the heat affected zone. Another factor that affects the hardenability is the cooling of the heat affected zone. If a fast cooling is chosen the size of the grain will have a relatively big, this means to increase the hardenability of the material. If a slow cooling is chosen, the opposite process happens, therefore the hardenability of the material decreases (Liu & Indacochea, 1990).

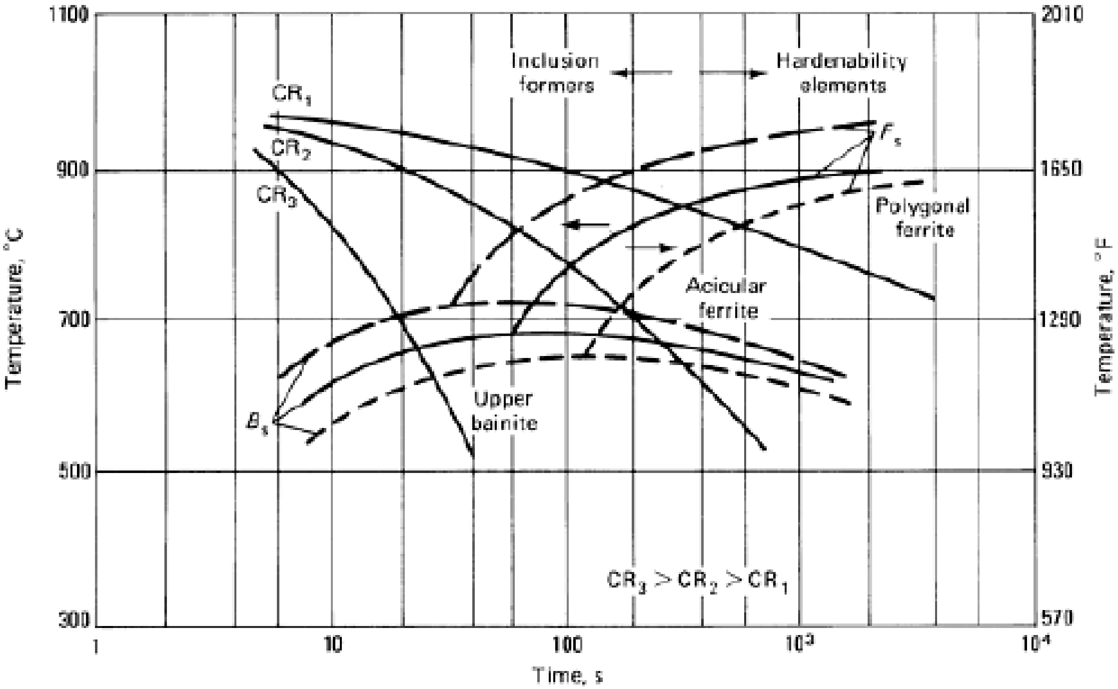


Figure 11. CCT Diagram (Liu & Indacochea, 1990).

Finally, some ideas about heat treatments will be exposed to end with the welding principles part. As it has been exposed previously, the cooling rate from the peak temperature defines the microstructure of the welded area, which defines the hardenability of the material. At the same time, the cooling rate affects the weldability of the material. This interlinking makes the cooling rate the most important factor. A slow cooling rate has some benefits, like avoiding excessive hardening and reducing the stresses. Equilibrium between the cooling and the hardening should be found in order to have the minimum weld cracking at the heat affected zone (Liu & Indacochea, 1990).

Brief information about welding plastics was thought to be included as part of the introductory preview of this report. It is very important to mention that only thermoplastics can be welded due to material properties, thermoset and elastomer cannot be welded (Swift & Booker, 2013).

Thermoplastics get soft and melt by rising the temperature, hence the welding methods are those where heat is applied at the contact area between both surfaces. This heat contribution produces either the fusion of both surfaces or turn them into a viscous state, resulting in joining two or more pieces into only one piece. The operator should be aware of the bad heat conductivity of this kind of plastics, due to the fact that whether a very high temperature is applied, instead of melting the plastic it can be burned. This result is produced due to the temperature rising is produced at a very high velocity and the burnt also affects the union quality by reducing its strength (Kalpakjian & Schmid, 2007).

Hereafter, an explanation of the structural state will be given to understand how the molecular structure of both plastic bodies became a unique body. If two bodies of the same polymer are in contact while these both surfaces are in a viscous or melted state, a unique body will be obtained by having intimate contact by intermolecular diffusion. This type of contact is not easy to obtain due to asperity peaks of the surfaces that affect this process even in very smooth surfaces. While the welding process is happening, these asperity peaks become softer and they tend to flow and filling the interstitial spaces (Grewell & Benatar, 2007).

When this first step is done, the material should be healed, which means that the two bodies or surfaces become only one body. However, the polymer molecules are not mixed between the two parts, therefore, some treatment needs to be done in order to achieve this state. In Figure 9 it is shown the perfect and ideal process, where the piece is completely healed. As it can be observed, there are some polymer chains of each piece crossing by the intersection and finishing in the opposite piece, which means that the union becomes indistinguishable. Finally, when this process is finished, the heat source is removed and the final piece is let to cooling. In this process, some residual stresses are generated due to the contractions and expansions that take place while the heat dissipation. Molecular orientation due to squeezing flow can affect the strength of the final weld, therefore, some attention needs to be paid to the residual stress to avoid weak welds, a descent of the fatigue life, or even an increase of the corrosive effects (Grewell & Benatar, 2007).

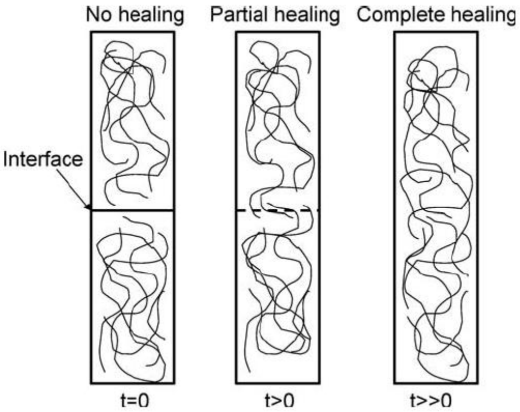


Figure 12. Healing process (Grewell & Benatar, 2007).

Appendix 2.3. Welding Techniques

As it was mentioned in the historical context previously exposed, there have appeared different welding techniques as the involved technology progressed. This section goes in depth in the principal welding types and describes them with more detail. This study is done in order to state the main features of every technique and distinguish laser welding advantages over the rest of the techniques, in view of the welding characteristics this project requires.

Appendix 2.3.1. Oxy-fuel Gas Welding

This technique is a manual process where the involved metal surfaces are gradually melted by a gas flame, which acts as the heat source and is able to reach greater temperatures than 3000ºC. The joint can be effectuated by either using a filler metal or not, without the necessity of applying pressure during the process (Cary, 1993; Swift & Booker, 2013).

The most important, common and simplest oxy-fuel gas welding system is the one which provides the melting heat by an oxyacetylene (OXA) torch. It consists of compressed gas cylinders, where the oxygen and fuel (acetylene) are separately stored. Each cylinder is connected to a hose by means of a gas pressure regulator. Both involved hoses end in the same nozzle, in which entry is placed a mixing chamber and in its tip the mixed gases go out forming the final flame (Cary, 1993).

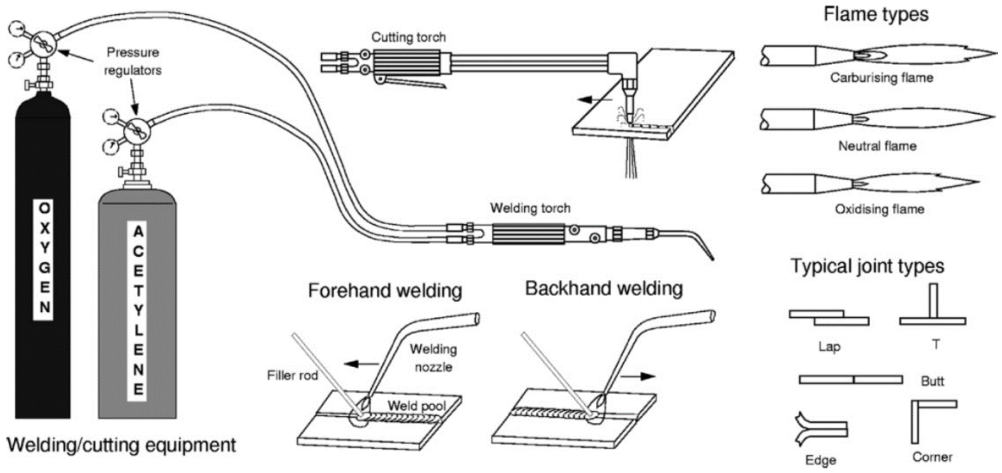


Figure 13. Oxy-fuel Gas Welding Equipment (Swift & Booker, 2013).

Materials (Swift & Booker, 2013):

- Ferrous alloys.
- Nickel, copper, aluminium alloys.
- Low-melting-point metals.
- Refractory metals cannot be welded.

Advantages (Swift & Booker, 2013):

- Simple system and welding technique.
- Flexible process (welding, cutting and several heat treatment processes).
- Economic process for low production runs.
- Short lead times.
- High-quality welds.

Limitations (Swift & Booker, 2013):

- Manual process.
- Surface preparation is needed.
- It cannot provide a large batch of production.
- Stress relieving treatment may be required.

Appendix 2.3.2. Tungsten Inert-Gas Welding (TIG)

This technique is carried out by maintaining an electric arc between the non-consumable tungsten electrode, which can reach a temperature of 12.000 ºC, and the workpiece that will be molten (temperature in the weld pool of about 2.500 ºC). During the process, a stream of inert gas protects the molten metal of the atmospheric contamination and prevents oxidation problems. This inert gas may be argon, helium or a mixture of both gases and the process can be developed either by using filler metal or not (Cary, 1993; Swift & Booker, 2013).

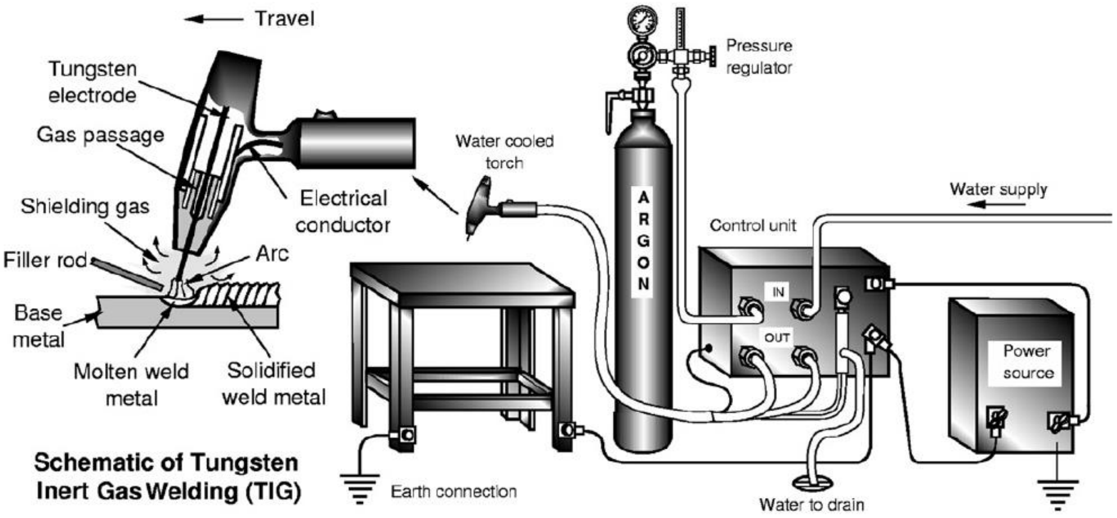


Figure 14. Tungsten Inert-gas Welding Equipment (Swift & Booker, 2013)

Materials (Cary, 1993; Swift & Booker, 2013):

- Most non-ferrous metals.
- Aluminium, nickel and magnesium.
- Reactive metals as titanium.
- Precious metals and refractory alloys can be welded.

Advantages (Cary, 1993; Swift & Booker, 2013):

- High-quality welding.
- Power regulation.
- Precise welding heat control.
- Economical for low production runs.
- Lower deposition than consumable electrode arc welding.
- It can be automatized for long welds in the same plane.

Limitations (Cary, 1993; Swift & Booker, 2013):

- Less economical than consumable electrode arc welding.
- High complexity of designs.
- Low tolerance for contaminants.
- Tungsten inclusions may appear.

Appendix 2.3.3. Manual Metal Arc Welding (MMA)

The following technique is the most widely used welding process due to its equipment requirements simplicity, even though it is a very complex technique to be carried out. This is a manual welding process where an electric arc appears between a flux-covered consumable electrode and the joint line of the workpiece. As the weld is being created by manually feeding the process with the consumable electrode, the flux melts and covers the weld pool, shielding it from atmospheric corrosion (Cary, 1993; Swift & Booker, 2013).

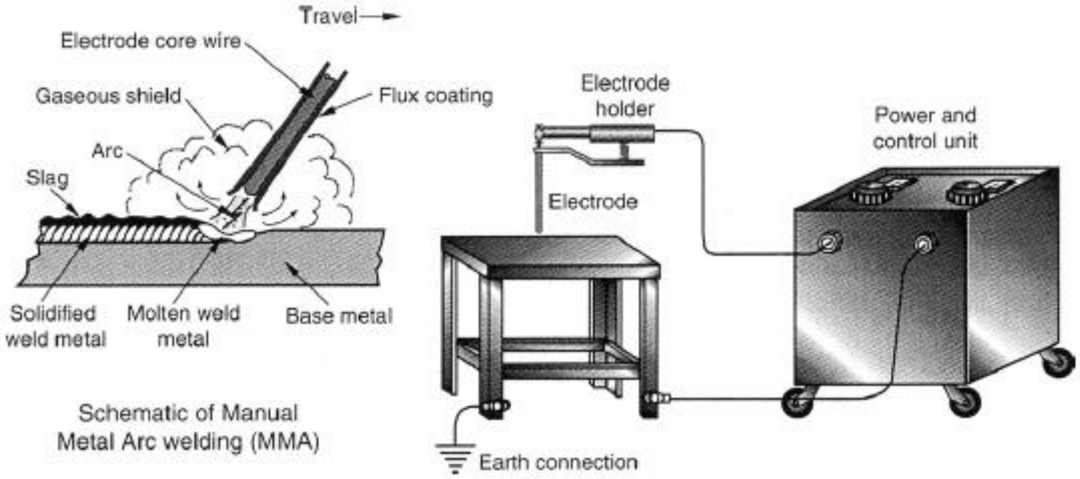


Figure 15. Manual Metal Arc Welding Equipment (Swift & Booker, 2013)

Materials (Swift & Booker, 2013):

- Nickel alloys
- Carbon low alloys
- Stainless steels
- Nickel alloys
- Not recommended for non-ferrous metals welding.

Advantages (Cary, 1993):

- Simplest equipment requirements.
- Greatest flexibility of all welding process.
- Easily available for all its applications.

Limitations (Cary, 1993):

- Complex welding technique.
- Quality is obtained according to the welder’s skills.
- An electrode replacement is needed when each consumable electrode runs out.

Appendix 2.3.4. Submerged Arc Welding (SAW)

This welding process is carried out by dispensing a flux blanket through a hopper and melting it with the use of an electric arc, which is created between a consumable wire electrode and the workpiece. The involved flux melts, shielding the weld pool and protecting it from the atmospheric corrosion and oxidation. The alloy ingredients presented in the flux must improve the mechanical properties of the final weld; furthermore, the flux that is not used during the process can be recycled (Cary, 1993; Swift & Booker, 2013).

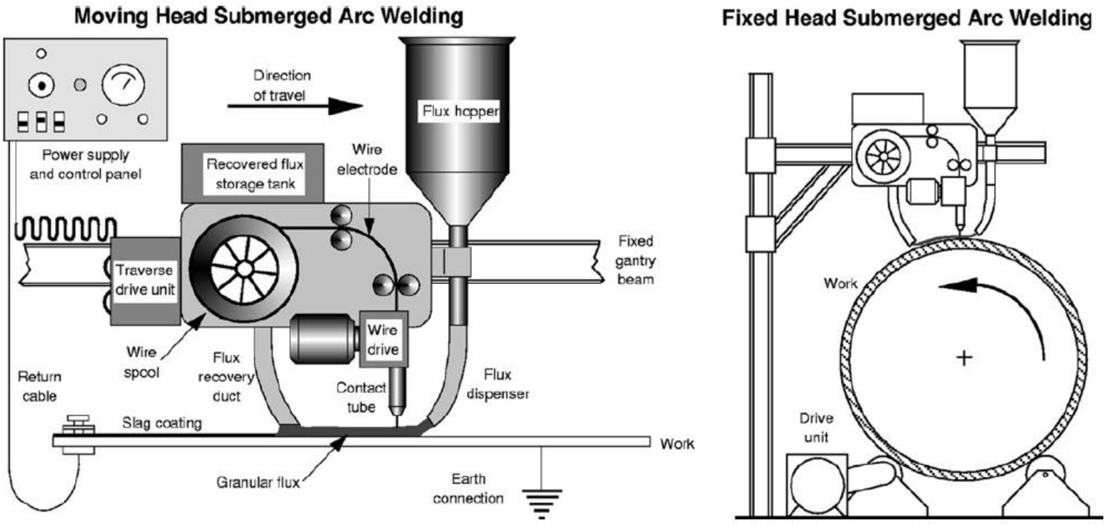


Figure 16. Submerged Arc Welding Equipment (Swift & Booker, 2013).

Materials (Swift & Booker, 2013):

- Some nickel alloys.
- Carbon low alloys and stainless steels.
- Not recommended dissimilar metals.

Advantages (Cary, 1993)

- Flux blanket prevents welding spatter, flash and fume. (Environmentally friendly)
- High deposition rates and welding speeds are possible.
- Cost per unit length of the joint is relatively economic.
- Minimum welder training is required.

Limitations (Cary, 1993):

- High initial cost of equipment and facilities.
- Only flat horizontal welding is possible.
- Deposited slag must be removed before each welding process.

Appendix 2.3.5. Electron beam welding (EBW)

This technique is a high-energy density fusion process carried out by projecting an electron beam into the workpiece to be welded. The involved electrons are accelerated up to 0.7 times the speed of light and thrown from an electron gun (cathode) to the working area (anode). The process is accomplished in a vacuum environment, which prevents the weld pool from impurities such as oxides (Cary, 1993; Swift & Booker, 2013).

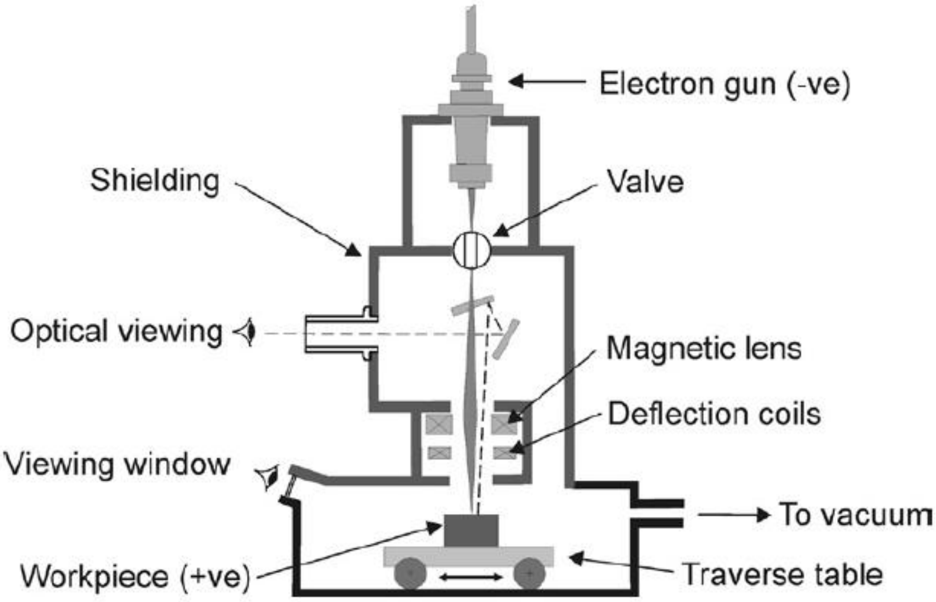


Figure 17. Electron Beam Welding Equipment (Swift & Booker, 2013).

Materials (Swift & Booker, 2013):

- Most metals including steels alloys.
- Aluminium, titanium, copper, etc.
- Refractory and precious metals.
- Metals which welding process presents problems of vaporization.

Advantages (Cary, 1993):

- Deeper and narrower than arc welds.
- Total heat input much lower than required in arc welding.
- Lower welding times.
- More energetically efficient.
- Not expensive process among other high-energy density welding processes.

Limitations (Cary, 1993):

- High cost of the equipment.
- Limitations of availability of the vacuum chamber.

Appendix 2.3.6. Plasma Arc Welding (PAW)

The next process is a gas-shielded arc welding technique where the arc is held between a non-consumable tungsten electrode and the workpiece, reaching temperatures until 20.000 °C. The plasma beam is produced by ionizing the gas and constricting it through a copper nozzle (Cary, 1993; Swift & Booker, 2013).

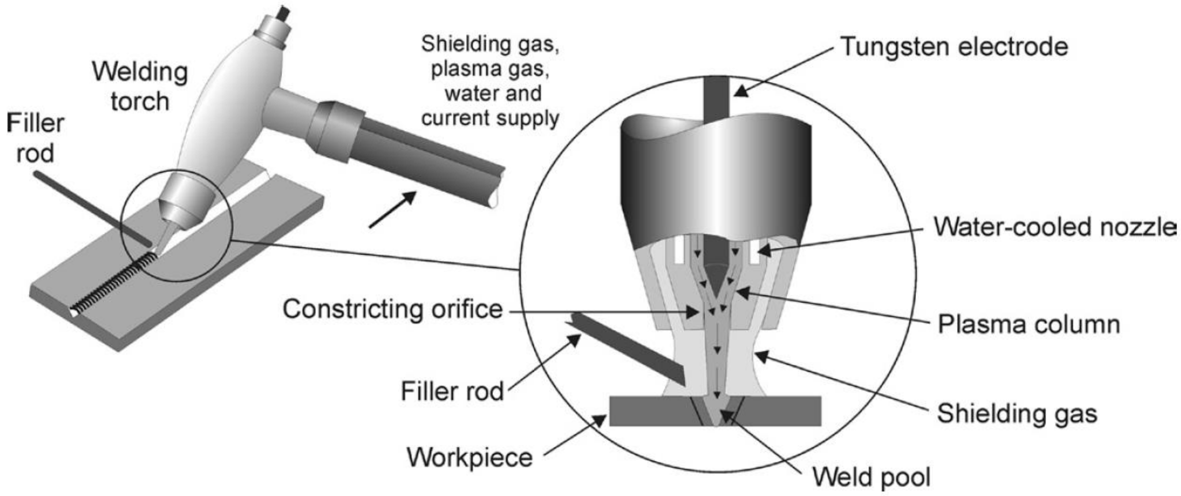


Figure 18. Plasma Arc Welding Equipment (Swift & Booker, 2013).

Materials (Swift & Booker, 2013):

- Aluminium, copper and nickel alloys.
- Refractory and precious metals.
- Electrically conductive materials.

Advantages (Swift & Booker, 2013):

- Profitable for low production runs.
- Tooling and process cost are low.
- Capable to weld really short thickness.
- High-quality welds, with great penetration.

Limitations (Swift & Booker, 2013):

- Expensive equipment.
- Design aspects are highly complex.

Appendix 2.3.7. High-Frequency Welding (HF)

This type of welding is based in the use of high frequency alternating current resistance heating as the heat source for welding, which permits an easy focusing to the zone of interest of the heat achieving outstanding results in welding (Cary, 1993).

Materials (Swift & Booker, 2013):

- Almost any material combination can be welded by this technique, commonly low carbon steels.

Advantages (Cary, 1993):

- Large range of materials can be welded.
- High-quality welding.
- Shielding process is not necessary.
- The process itself reduces and removes residual oxides.

Limitations (Cary, 1993):

- It cannot be operated at low speeds.
- The process cannot be interrupted or developed with stop/start operations.

Appendix 2.3.8. Laser-beam Welding (LBW)

Laser (light amplification by stimulated emission of radiation) welding technique uses high-density optical energy as the heat source, which is directed and focused to the workpiece by lenses and mirrors that permits to concentrate the beam to a small spot. This capability will be really useful in developing the welding studied in this report (Cary, 1993; Swift & Booker, 2013).

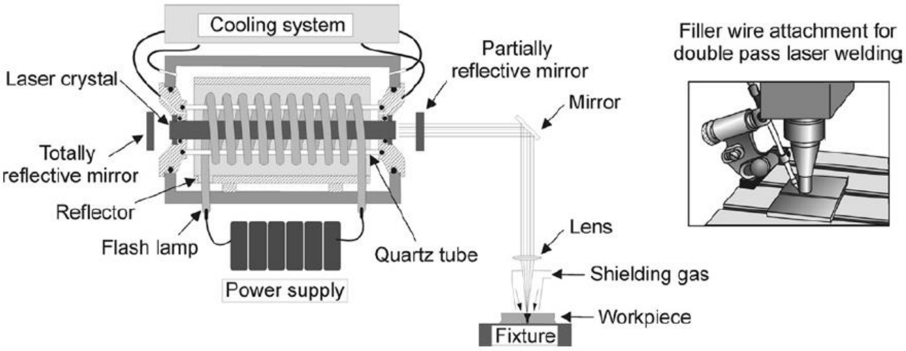


Figure 19. Laser-beam Welding Equipment (Swift & Booker, 2013)

Materials (Cary, 1993; Swift & Booker, 2013):

- A large variety of metals and alloys can be welded.
- Commonly for stainless steel.

Advantages (Cary, 1993; Swift & Booker, 2013; Cao, et al., 2003):

- High-speed welding process, with the possibility of very rapid stop/start interruptions
- It is not necessary for a protective atmosphere.
- No electrode or filler material is necessary.
- Precise and narrows welding.
- Free contamination welding.
- Flexibility: cut process is also available.
- Accurate and low heat input, therefore it produces a smaller HAZ.
- High depth/width ratio.
- Permits to weld a great range of materials.

Limitations (Cary, 1993; Swift & Booker, 2013):

- Weldability depends on the thermal conductivity, hardness, chemical compositions and optical characteristics of the involved material.

Appendix 2.3.9. Other welding techniques.

In spite of the techniques already named, there exist other remarkable welding processes to be mention in this study. Hereunder several welding processes to take into account will be exposed and briefly described:

- Ultrasonic welding. The welding process is carried out by inducing high-frequency into the union to be weld, achieving a low level of molten material. Ultrasonic welding permits the union of a wide range of different materials including thermoplastic. (Swift & Booker, 2013).
- Friction welding. Two parallel surfaces are welded by means of a relative rotational movement of one of them onto the other surface. The axial force is increased in order to magnify the pressure of the contact and reach a temperature high enough to weld the parts involved. This technique is not widely used due to its lack of flexibility (Swift & Booker, 2013).
- Explosion welding. This technique uses the energy and heat released by a controlled explosion to accomplish an electron-sharing bond between the metals to be weld. The heat involved in the process cannot be released by heat transfer mechanisms, accordingly, there is no heat-affected zone in the final weld, and no changes are induced into the weld metals, therefore no continuous weld is found after the process (Swift & Booker, 2013).

Appendix 2.4. History of laser welding

In this appendix, some historical facts and basic concepts about one technique previously introduced, the laser welding technique will be explained. The laser beam welding generates the joint with the heat produced by the laser beam impacting against the joint. Normally the weld is generated by itself, therefore, is not usual to use a fillet metal (Kautz, et al., 2007).

Before talking about laser welding a brief introduction about the use of laser is going to be given in order to create the appropriate historical context. Laser was created at the 1960s, the first model used an electrically excited ruby crystal. At latest 60s, this laser completed its first successful experiment, performing the first laser material manufacturing. This kind of laser that has a solid crystal has some limitations due to the heat capacity of the crystal, affecting to the frequency of the pulses and to the peak power that can be used (Kautz, et al., 2007).

At the end of the 70s, other kinds of lasers were being developed. These lasers were the semiconductor lasers, which were manufactured with a double crystalline heterostructure. The implementation of this improvement supposed the reduction of the continuous wave threshold. These crystals were manufactured by using a method called liquid phase epitaxy (LPE) however, this method has some imperfections. The main disadvantage was that the crystal was not homogeneous, limiting some parameters of the laser as the aperture size. Meaning that the efficiency of the laser decreases and it could only work with a few mW as the input power. As a result, it could only be used in not very challenging manufacturing processes (Welch, 2000).

As it was explained above, the first laser technology did not have power enough to develop stressful manufacturing. Therefore, processes as welding could not be done, however, some evolution in this field finally allowed that these types of processes could be done. Accordingly, other methods used to manufacture the crystals were invented like the metalorganic chemical vapour deposition (MOCVD) and molecular beam epitaxy (MBE). The advantages of these two methods essentially, balance out the main disadvantage of the previous method. Allowing the formation of a more uniform crystal by controlling the deposition of the material at an atomic level. This indicates that more mW could be taken as the input power and higher aperture size could be used. Hence, more stressful applications can be developed with the laser as the output power increases (Welch, 2000).

These two new methods changed everything at this field due to the possibility of controlling the deposition of the material at an atomic scale. Some improvements were made and a new type of laser appeared, it was called quantum well laser. This new type of laser had some advantages, like the reduction of some carrier loss and mainly the reduction of the temperature sensitivity of the threshold current, also reducing this last one (Welch, 2000).

This means that the lowest excitation level that can be dominated by the laser is lowered, therefore, the temperature decreases and the efficiency of the laser is increased. At this stage of the development, the lasers were able to make stressful operations like laser welding. They were able to develop a higher output power with an efficiency of 60%, making these semiconductor lasers the ones with the highest efficiency for these applications (Welch, 2000).

The first developed laser welding methodology was the CO_2 laser. This kind of laser was invented in 1964, as it was mentioned before by this time the lasers did not have enough power to make welding operations. Therefore, some years later around 1966 was when the first commercial laser was put in the market. After many years some improvements were made increasing the output power of the laser up to 50 kW, converting this method into a high power laser one. The wavelength of the laser increased until it was ten times bigger than the value of the solid-state laser beams. Probably, this is one of the most important parameters of the laser because it defines the materials that can be manufactured. Hence, it defines the characteristics of the final weld, also defining the shielding gases that should be used (Katayama, 2013).

Once the CO_2 laser type was invented, some research was done at other gases, ending with the Nd-YAG laser invention (*neodymium-doped yttrium aluminium garnet)*. Essentially, the advantages of this method were the wider wavelength spectrum and the higher reliability that was achieved. This is the reason why these lasers are the most used at the welding operations. However, until 1970 they were limited by the thickness of the materials, the available power and the time need to make the weld. Therefore, before this date, laser welding was used to make very small welds at the electric field as in motherboards and another kind of system boards. When these two types of lasers appeared and were improved, these limitations disappeared, giving way to the deep penetration welding (Swift & Booker, 2013).

Later on more types of laser welding appeared, but this will be exposed at the types of laser discussion. As a summary, laser welding has been implemented in different industrial fields due to its flexibility as well as the high quality and precision achieved by performing this technique, "which facilitates automation, power saving and systematization" (Katayama, et al., 2009).

Appendix 3. Principles of laser welding

Appendix 3.1. Material properties that affect the welding process

The outcomes presented in the paper called *Laser welding; the influence of laser choice and material properties on weld dimensions* belong to an experiment carried out by the authors of the forenamed paper. In this experiment, three kinds of metals were welded under similar conditions by two different types of laser beams (Nd:YAG laser and CO_2 laser), obtaining distinct weld shapes and sizes. By analysing the width of these welds, four material properties are defined to affect the weld dimensions (Forsman, et al., 2001).

This appendix explains the phenomena shown in Section 2.1. At first, the phenomenon of absorption during the welding process will be described. As it is said in Section 2.1, there exist two different means of absorption that take place meanwhile welding is being accomplished: direct absorption and keyhole absorption.

Direct absorption depends on the melt surface condition and the impact angle (laser beam direction and weld surface). Both features remain similar for both laser beams involved in the experiment, however, there exists another main parameter which makes a difference in both laser beam absorptivity. The wavelength of the Nd:YAG laser light is much shorter than the one presented in CO_2 laser light, therefore the Nd:YAG laser beam will present a greater absorptivity than the CO_2 laser beam, as it is remarked in the original reference "the absorptivity for Nd:YAG laser light is approximately twice that for CO_2 lasers" (Forsman, et al., 2001). A representation of the absorptivity of both laser lights by different metals as a function of the angle of incidence is shown in the next plot (Forsman, et al., 2001):

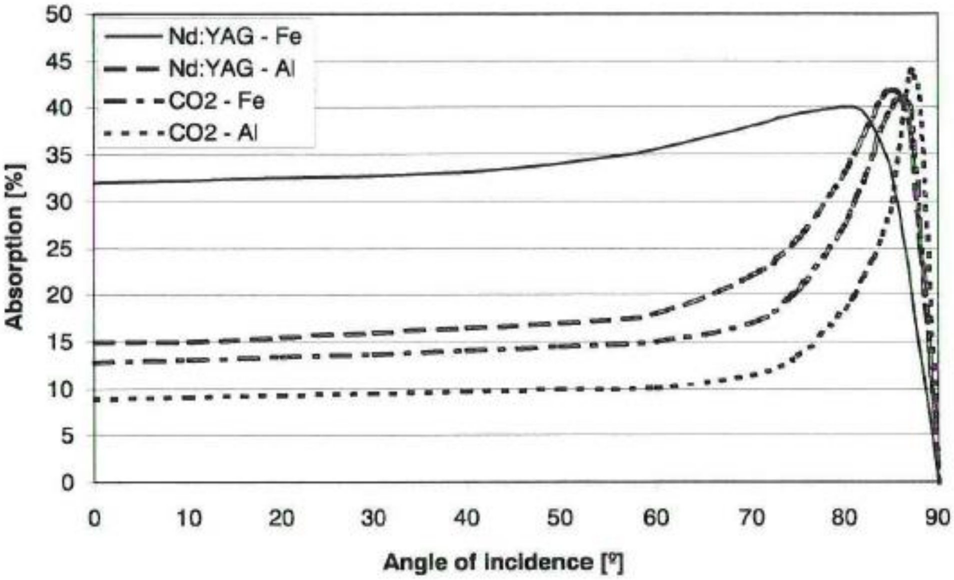


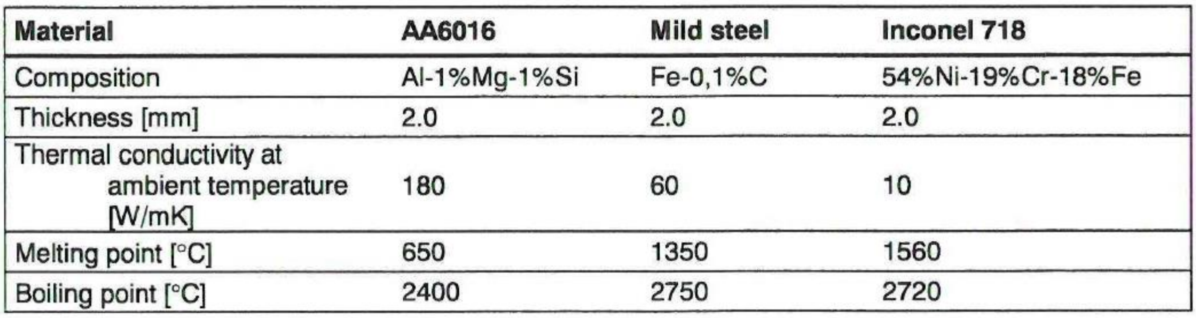
Figure 20. Absorption as a function of angle of incidence, where 0º is the perpendicular direction to the involved surface (Forsman, et al., 2001).

Once the direct absorption has been analysed, the next phenomenon to focus on is the energy absorption of the metal vapour in the keyhole. This vapour within the keyhole will present ionization to some extent becoming into plasma (Forsman, et al., 2001).

As it is referred, “the absorption of light by an ionized vapour is proportional to the square of the wavelength of the light” (Forsman, et al., 2001), therefore the CO_2 laser light will be greater absorbed than Nd:YAG laser light by the ionized vapour, concretely in the order of 100 times greater, since the CO_2 laser light wavelength is 10 times larger than the one of Nd:YAG laser light. This phenomenon explains the reached depth by both laser types, since an important percentage (10-40%) of the energy of the laser beam is absorbed by the ionized vapour at the top of the keyhole when using CO_2 laser, not letting the beam penetrating deeper; meanwhile the energy absorbed by the plasma in the keyhole when using Nd:YAG laser is negligible (0.1 - 0.4%), so the beam reaches a larger depth during the penetration. It should be noted that the energy absorbed by the plasma during the process will be re-radiated in every direction, wasting part of the energy contributed by the laser beam (Forsman, et al., 2001).

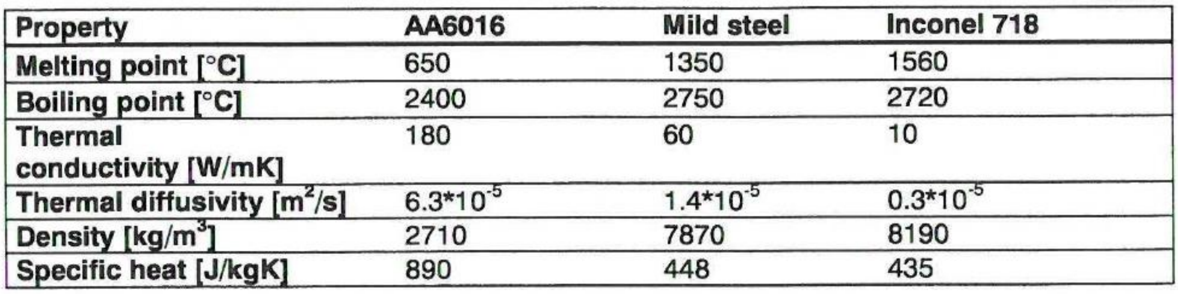
Since the absorption efficiency of the Nd:YAG laser is greater than the one presented with the CO_2 laser when welding, the dimensions (width, depth…) of the created welds by Nd:YAG laser will be larger than the ones appearing with the CO_2 laser, in addition to a greater amount of melt volume in the weld pool (Forsman, et al., 2001).

To continue, the material selection consequences are going to be studied, in order to determine what features of the material to be welded affect the dimensions of the final weld. Two similar welding operations were carried out to three different metals with the same dimensions, using both of the already described laser kinds. The materials involved are described by the next features (Forsman, et al., 2001):



Material	AA6016	Mild steel	Inconel 718
Composition	Al-1%Mg-1%Si	Fe-0,1%C	54%Ni-19%Cr-18%Fe
Thickness [mm]	2.0	2.0	2.0
Thermal conductivity at ambient temperature [W/mK]	180	60	10
Melting point [°C]	650	1350	1560
Boiling point [°C]	2400	2750	2720

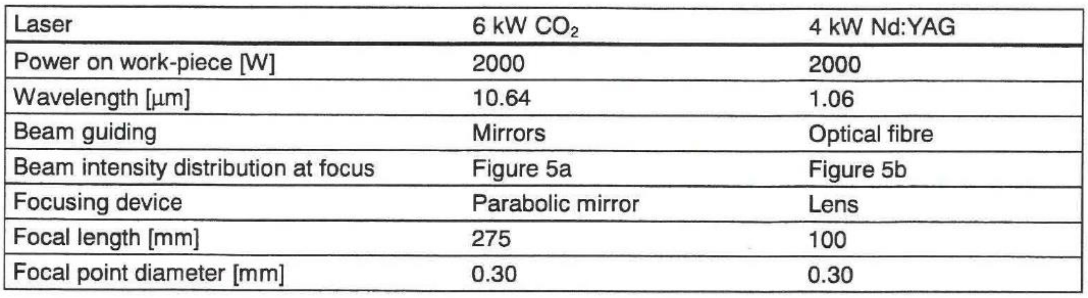
Table 3. Material properties of the three involved metals (Forsman, et al., 2001).



Property	AA6016	Mild steel	Inconel 718
Melting point [°C]	650	1350	1560
Boiling point [°C]	2400	2750	2720
Thermal conductivity [W/mK]	180	60	10
Thermal diffusivity [m^2/s]	$6.3*10^{-5}$	$1.4*10^{-5}$	$0.3*10^{-5}$
Density [kg/m^3]	2710	7870	8190
Specific heat [J/kgK]	890	448	435

Table 4. Material properties of the three involved metals (Forsman, et al., 2001).

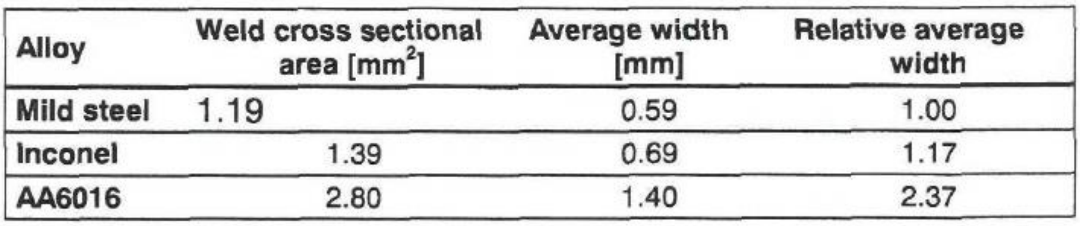
Meanwhile, the welding processes accomplished with a speed of 2 m/s are described by the following characteristics:



Laser	6 kW CO_2	4 kW Nd:YAG
Power on work-piece [W]	2000	2000
Wavelength [μm]	10.64	1.06
Beam guiding	Mirrors	Optical fibre
Beam intensity distribution at focus	Figure 5a	Figure 5b
Focusing device	Parabolic mirror	Lens
Focal length [mm]	275	100
Focal point diameter [mm]	0.30	0.30

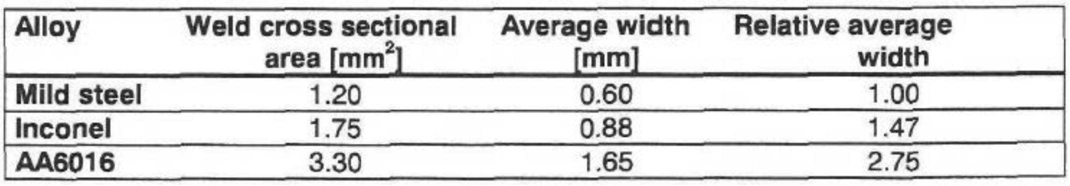
Table 5. Laser information (Forsman, et al., 2001).

The final outcomes present mean values of the appearing dimensions in all the six cases, giving global information about the influence of the material properties on the size of the obtained welds. This means dimensions are summed up in the next tables (Forsman, et al., 2001):



Alloy	Weld cross sectional area [mm^2]	Average width [mm]	Relative average width
Mild steel	1.19	0.59	1.00
Inconel	1.39	0.69	1.17
AA6016	2.80	1.40	2.37

Table 6. Relative average weld widths of the CO_2 laser welds (Forsman, et al., 2001).



Alloy	Weld cross sectional area [mm^2]	Average width [mm]	Relative average width
Mild steel	1.20	0.60	1.00
Inconel	1.75	0.88	1.47
AA6016	3.30	1.65	2.75

Table 7. Relative average weld widths of the Nd:YAG laser welds (Forsman, et al., 2001).

Finally, the influence of these material properties on the final weld is briefly exposed next:

- Specific heat and density are related to the maximum temperature reached during the welding process. These parameters are inversely proportional to the peak temperature, which has direct effects on the width of the produced weld, forming a greater heat-affected zone as it increases (Forsman, et al., 2001).

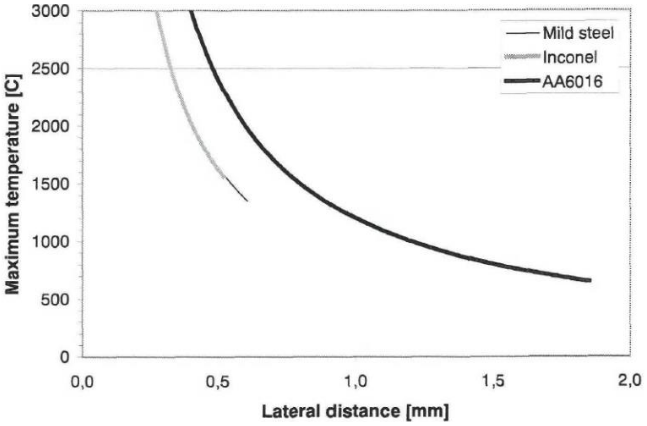


Figure 21. The maximum temperature reached as a function of lateral distance from the weld centre line. The curves end at the materials' respective melting points (Forsman, et al., 2001).

- The next feature affecting the weld shape and size is electrical conductivity, which is related to the absorption of the laser light within the keyhole as it is shown hereunder (Forsman, et al., 2001):

$$A \propto \frac{1}{\sqrt{\sigma}}$$

where

A = absorptivity
σ = electrical conductivity [A/Vm].

Figure 22. Relationship between absorptivity and electrical conductivity (Forsman, et al., 2001).

  As the expression above shows, the absorption taking place during the welding process will increase as the electrical conductivity decreases and, therefore, the width presented by the final weld will be larger as the electrical conductivity decreases (Forsman, et al., 2001).

- The last parameter of the material to take into account in order to know the shape of the final weld is the melting point of the material. As the melting point temperature of the material to be weld decreases, the appearing molten material will increase and, therefore, the final weld will present a larger size as this parameter decreases (Forsman, et al., 2001).

The outcomes presented in the aforementioned paper show that the aluminium alloy resulted to be the material with bigger dimensions on its welds due to its mechanical properties.

Appendix 3.2. Types of joint

The next principle is about the types of laser welding joints. These techniques follow the same criteria and shape of general welding. The unique difference is the special case when highly reflective materials are welded, therefore the shape of the joint should help to concentrate the laser or energy at the point of welding (Kautz, et al., 2007).

Consecutively some types of joint are going to be described, they can be observed in Figure 22. The analysis is going to be started with the butt joint. This type of joint can be done with different types of geometry that can be annular, circumferential or linear. Some parameters are very important in butt welds developed with laser welding. For instance, the previous fit up in order to create a well-balanced union, also the cleanliness of the joint has to be guaranteed by removing all the dirt that could be at the pieces and at the area that is going to be welded. In addition, some attention should be paid to the root openings because if these are too wide some underfill could be created (Kautz, et al., 2007).

This kind of welding can be easily adapted to production operations, especially if it is desired to automate the process. However, some points have to be taken into account like hold down tools to guarantee the intimate contact to achieve the dimensional control required. If the annular butt weld is done in order to get some independence at the process, the subassemblies can be simplified due to the fact that the welding has less importance with this preassembly, also the tolerances are improved (Kautz, et al., 2007).

The next type of joint that is going to be discussed is the corner joint. This type of joint is used in some assemblies and for sealing applications. Should be noted that this technique has some limitations. The main one is that it is very dependent on the thickness of the plate, entailing that the power should be adjusted. This means that if the plate thickness is small, the power has to be lowered and whether the plate thickness is thicker the power of the laser should be raised. It signifies that the power of the laser is proportional to the thickness. The corner joint has some advantages like the better accessibility while manufacturing it, and this is very important in order to maintain the integrity of the fit up (Kautz, et al., 2007).

The next type of joint discussed is the T-joint. If the laser is focused at an optimum angle, this laser should be focused at the way of the root opening happens. As in the previous method, the used power of the laser is proportional to the plate thickness. While the process of welding the stress is transmitted from one element to another because in some configurations, the laser impacts only to one element and it transmits the energy to the next one. If the weld is a fillet instead of a point the stress will be reduced (Kautz, et al., 2007).

Finally, the last type of joint that is going to be explained is the lap joint. The main application of this technique is for sheet metal assemblies, therefore the laser is focused at the first sheet or at the top of the surface and it penetrates in all the metal sheets. In contrast with the other types of joints, it does not require intimate contact between the parts. The melted metal will move downward through the sheets and join them. To establish some gap between the parts is a great option to not trap welding gases, produced by the melted material, especially when some special materials like coated metal are being welded. As in other types of joint, the stress concentration area is the welded zone. If the size of the final weld needs to be incremented, the pattern of the welding can be changed from a circular pattern to a linear one, just by changing the focus point of the laser (Kautz, et al., 2007).

In the previous cases, the importance of the fit up of the different pieces was discussed. Nevertheless with a lap joint, this factor has not that grade of importance, it is only needed to maintain the fit up with some tooling. Usually, in this case of joint, some reinforcement is needed at the fusion zone or at the weld roots. This is justified because sometimes the last sheet is not welded or penetrated by the laser or the melted material. Therefore, a resulting deformation is produced at the bottom surface due to heat distortion, generating a joint defect due to an incomplete penetration. Finally, this is the type of joint is less affected by the location of the welding point, compared to the previously discussed types (Kautz, et al., 2007).

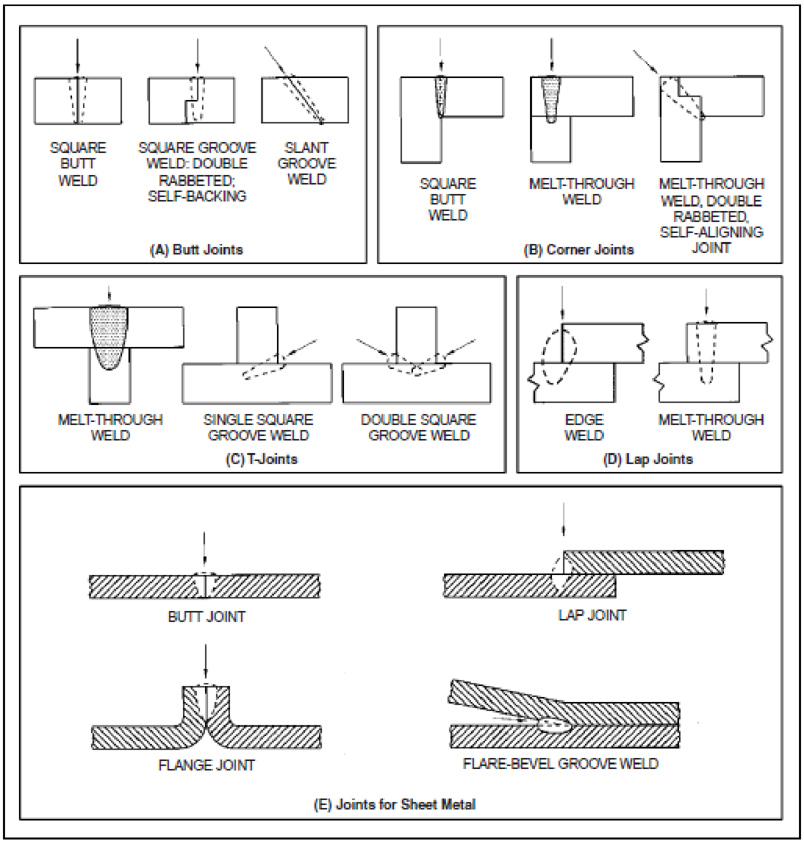


Figure 23. Joint Types (Kautz, et al., 2007).

Appendix 3.3. Metals welded

In order to complete the information presented in Section 2.2, some groups of materials that may be welded by using laser welding are hereunder shown:

- Copper and brass can be welded to their selves or to other types of metals using conduction welding, which will be explained in Section 3 of this report. These materials can also be used to accomplish special types of joints (Kautz, et al., 2007).

- Refractory metals. A special methodology could be needed in order to achieve a high-quality result. Essentially, this kind of materials are used in electronic assemblies or components, therefore some examples of these materials are tungsten and nickel. These materials are welded with the conduction method in order to avoid residual contamination on the final weld. Other materials like titanium would need a special protective atmosphere in order to avoid oxidation (Kautz, et al., 2007).

- Dissimilar metals. As the previous case, this procedure is done by using the conduction mode, with the particularity of twisting the conductor in order to improve the electromagnetic compatibility and to reduce the bending to avoid brittle joints. The quality of the weld also depends on the difference between the properties of both materials such as conductivity, melting temperature, and reflectivity; therefore, some special techniques can be used to achieve an equilibrium between both materials. For example, adding extra material to the joint area may help to achieve more similar properties and can balance the melting characteristics of both materials (Kautz, et al., 2007).

Appendix 3.4. Defects and how to avoid them

Hereunder an explanation of a wider variety of defects can be found. These defects are different to the ones explained at the homonymous section of the report. The information is extended in both external and internal defects.

Starting with external defects, welding deformation happens due to some factors about the high temperature that the material suffers while the welding operation is being done. Essentially the material suffers phenomena like fusion and vaporization. In addition, if these facts are related to the high temperature of the process, the material also suffers expansions and contractions that affect the dimensions of the piece. If all these cases are taken into consideration it can be established that the material suffers some deformations, hence some stresses are generated. This kind of deformation is going to appear almost always especially when two factors are accomplished. The first one corresponds to high thermal expansion coefficients of the materials that are being worked, and the second one is if the material is shaped in the form of a sheet. If this kind of defect wants to be avoided some measures can be taken like using the appropriate hold down tools, fast cooling, or cooling the welded product at room temperature (Katayama, 2013).

The next defect discussed is the poor appearance of the laser weld. The main problem of the surface the exposition to high temperatures. This means that a protective atmosphere is needed to protect the molten pool and the near vicinity area from oxidation, deposition of particles and sparkles. Moreover, the colour of the piece can have some variations depending on the material and the temperature. If some spatters appear at the final result this is considered as a poor surface appearance. If this defect is desired to be counteracted, some actions can be done, for instance, using a shielding gas in the correct amount in order to avoid some depositions at the welding zone. Another option is to reduce the laser spot until it is small compared to the molten pool size. The enlargement of the keyhole inlet and the use of proper laser inclination and a vacuum environment are valid solutions too (Katayama, 2013).

Changing now to internal defects, another example of it is the incomplete penetration of the laser beam. Mainly this defect appears when a keyhole joint is being done because it is the deepest type of joint. It could be the case where the laser beam does not arrive until the end of the joint, meaning that a conduction joint is done instead of a keyhole one (more information about the laser welding modes can be found at Section 3 of the report) (Katayama, 2013).

The aspects that boost incomplete penetration are high thermal conductivity and reflectivity. Aluminium is a material that accomplishes both requirements. Usually, an argon-based shielding gas is used to weld this material, however it should be changed to some helium shielding gas. Otherwise, the wavelength of the laser beam should be changed to 1 µm. If the welding process is being done with multiple passes and the welded area is not along the whole joint the power of the laser should be increased (Katayama, 2013).

The next defect that is going to be explained is about the evaporation of the alloying elements. This happens due to the high temperatures that are achieved during the welding process and especially if the alloying elements have a lower melting temperature. This evaporation always occurs but should be reduced by increasing the speed of the process or by adding these alloying elements using a filler wire (Katayama, 2013).

Moreover, another defect that can be mentioned is the macrosegregation. It is a common defect presented when materials of different chemical compositions suffer a laser welding process, usually when a filler metal wire is used. This defect consists in a discontinuous deposition of the material in the gap to weld, affecting the weld fusion zone. Macrosegregation depends on the size and shape of the gap to fill; the wider it is at the bottom the greater the penetration will be and the macrosegregation will be reduced. A way of prevention is mixing the molten pool material to facilitate a continuous deposition (Katayama, 2013).

The last defect to talk about is microsegregation, which consists in the solidification of a determined component in the molten material when a fusion welding process is being applied. This defect takes place in alloys and materials presenting impurities in a lower concentration than the containing matrix. Usually, it yields in cracking defects in addition to a reduction of strength and hardness in the weld zone. A way to prevent these harmful effects is applying a heat treatment when the union is done (Katayama, 2013).

Appendix 3.5. Quality or property defects

Hereunder it is shown a table where the hardness presented in the worked weld is described, as well as the prevention or solution process to improve the joint properties in each case (Katayama, 2013).

Metal kind	**Weld properties**	**Prevention/solution**
Normal carbon steels	The welds present an increment of hardness due to the formation of harder phases of steel.	No kind of prevention or solution process is necessary due to the appropriate response of welds.
Tempered high tensile strength steels	The weld fusion zone suffers a reduction of hardness due to porosity formation.	A high-speed welding process will prevent the formation of porosity within these welds.
Age-hardenable alloys (aluminium alloys, nickel alloys, copper alloys…)	The weld fusion zone suffers a reduction of hardness due to the suppression of hardenable phases by melting and reduction of precipitation of hard phases due to microsegregation.	A heat treatment, such as ageing treatment, is needed to be carried out to fully recover the joint properties.
Annealed base alloys (A5052, A5083, A5182…)	The weld fusion zone suffers a greater reduction of hardness due to porosity formation.	A high-speed welding process will prevent the formation of porosity within these welds.

Table 8. Summary of weld properties and processes for the prevention of defects after laser welding (Katayama, 2013).

Appendix 4. Additional Welding techniques

In this appendix, supplementary information about the welding modes is added. The welding modes included at this appendix correspond to Section 3.3 of the report adding more detailed information about them.

Appendix 4.1. Shallow-Penetration Welding

When the conduction welding mode is accomplished with an output power under 1kW, and speed near to the depth-of-fusion limit is called shallow penetration welding. This limit represents that the effects of thermal conduction are more significant than the effects of deep welding processes such as keyhole welding (Kautz, et al., 2007).

This kind of welding has as outcomes a conduction weld with little or none keyhole created and a larger weld bead. Shallow welds are widely used in sealing applications, as well as enclosure welds for electronic items and batteries (Kautz, et al., 2007).

It is possible to reduce and adjust the welding speed in order to obtain the required width and depth of weld, according to the workpiece conditions and its purpose (Kautz, et al., 2007).

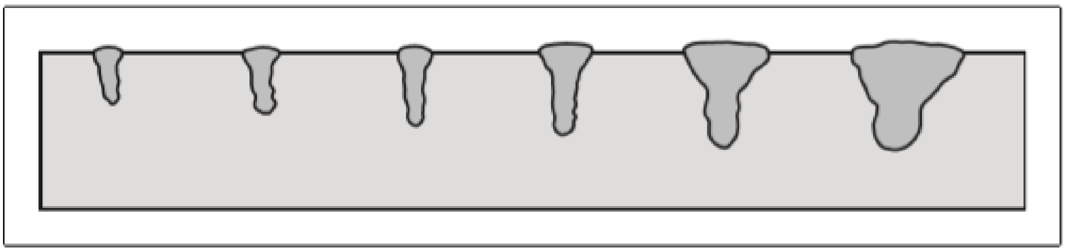


Figure 24. Variation of Weld Penetration as Travel Speed Changes Using Continuous-Wave Output Power (Kautz, et al., 2007).

Appendix 4.2. Pulsed Laser Beam Welding

Pulsed laser beam welding is an excellent joining process to be carried out when joining thin surfaces is desired. As in most welding processes, it is favourable to achieve a complete penetration union. Therefore, reducing the tolerance distances and avoiding mismatches in the setup is really important due to the dimensions of the surfaces to be weld and the size of the produced welds. Table 9 shows the advantages and limitations presented when accomplishing this technique (Kautz, et al., 2007).

Advantages	**Limitations**
Small heat-affected and fusion zones	High cooling rates
Low heat input	Sensitivity to material chemistry
Precision welding	Problems with highly reflective materials

Table 9. Advantages and limitations of pulsed laser beam welding (Kautz, et al., 2007).

Both high cooling rates and material chemistry are factors that may provoke cracking in the workpiece weld by pulsed laser beam welding. However, this defect can be avoided by practising a pre-heat process on the workpiece and changing the wavelength of the beam, which helps to decrease the cooling rate. The last option should be selecting a better material to accomplish the weld according to the future application of the welded piece (Kautz, et al., 2007).

For aluminium alloys, continuous wave laser represents a better solution than a pulse wave laser for different reasons (Kautz, et al., 2007):

- Lower initial and operating costs.
- High-quality performance, achieving stable welding and avoiding different harmful defects such as undercut, porosity or cracking.

Appendix 4.3. Hybrid Welding

This welding process brings laser welding and gas metal arc welding features into only one process in order to achieve better outcomes in efficiency and productivity. Usually, the main heat source is the laser beam and the arc acts as the secondary one, at the figure below the distribution of the heat sources can be observed. When adding laser welding technique to the GMAW process, a growth of the welding speed is obtained due to the improvement on the wetting of the weld pool. In addition, better stability of this weld pool is achieved. It is important to remark that both aluminium alloys and steels are possible to be welded by this process achieving high-quality results. Making it a reliable process to be accomplished in most engineering industrial unions (Kautz, et al., 2007; Katayama, 2013).

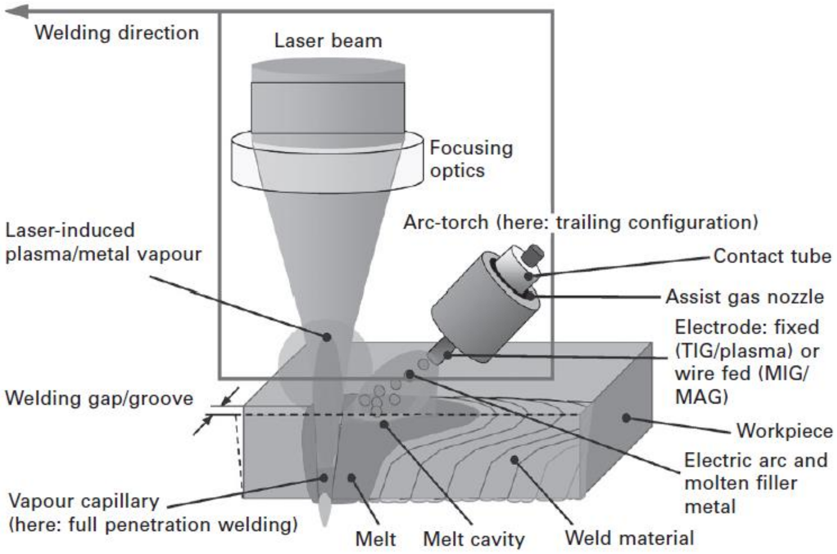


Figure 25. Hybrid welding equipment and distribution (Katayama, 2013).

As it can be observed at the figure above, both techniques are applied at the same time and both sources are moving together along the joint working of the same melt pool. By using hybrid technology, the main advantage that it is achieved is having more flexibility. This improvement refers to the control of the process in the fields of power and speed in function of the material used (Katayama, 2013).

As it has been established before the arc works as an additional heat source, however it can be used to add filler material too. This is not the unique hybrid method but is the most used one in the industry specifically at shipbuilding and automotive industry. Other hybrid methods are developed with TIG instead of GMAW, or MIG. The discovery of the last technique definitely boosted the use and development of other hybrid techniques due to its reliability. At Table 10 the advantages of this method compared with the laser beam welding and metal arc welding will be exposed (Katayama, 2013).

Laser Beam Welding	Metal Arc Welding
Thermal cycle more adjusted	Increased welding speed
Lower fitting and clamping requirements	The distortion is decreased
Increased bridging capability with less power	Heat input is decreased

Table 10. Comparison of both laser beam welding and metal arc welding (Katayama, 2013).

In conclusion, the hybrid process is done to obtain more flexibility as it was said before, also the quality of the weld is increased. However, the productivity is mainly improved because of the speed is increased too (Katayama, 2013).

Appendix 5. Sustainability of Laser Welding

At this point of the report, the sustainability of the laser welding process will be discussed. The study will be focused on environmental impact and safety of the welders. This information has been subtracted from a study where laser welding is compared with some other techniques hereunder mentioned.

Comparing laser welding to the most common techniques as metal arc welding, some conclusions may be obtained about emissions. Laser welding has the least energy consumption working at the same speed and also fewer fume emissions. Mostly welding operations produce some fumes that are a mix of some particles and substances. Essentially, these gases are volatilized metals that can be harmful to the human being producing lung, kidney and heart diseases. These gases are mainly iron oxides, chromium, nickel and manganese. In general, the workers are more affected in the manual works than in the automated ones, this makes very important the way the process is designed and the development of the protecting equipment (Chang, et al., 2015).

The environmental impacts can be summed in four fields: atmosphere acidification, global warming, creation of photochemical ozone and eutrophication. In order to give some magnitude to the results, the impact generated by the laser beam welding will be compared with the one that is generated by metal arc welding. The manual metal arc welding is the technique with the highest impact at the four fields, and the laser beam welding has the lowest impact at the four fields (Chang, et al., 2015).

The laser welding is one of the most ecological techniques for several reasons; it is the technique with the highest power, which allows making the welding process with less number of passes, a quicker process and reaching high productivity. These three reasons reduce the fume emissions. The other techniques are slower or use filler material which increases the impact at some of the fields mentioned earlier. Furthermore, the manual process has higher emission due to the lack of precision and lower speed. As a conclusion, the laser welding process is the most environmentally friendly process due to the fact that it owns the least electricity and material consumption per 1 meter of weld (Chang, et al., 2015).

Appendix 6. Aluminium welding

Hereunder are exposed in detail the main mechanical properties affecting the weldability of aluminium and its alloys. These mechanical properties will be decisive to choose the final welding mode to be applied.

Appendix 6.1. Thermal conductivity

This property affects the velocity of the heat transfer process; the greatest thermal conductivity presented by the material, the faster it dispels the thermal energy. A high thermal conductivity of the material to weld entails trouble, as it does not permit the energy to be focused on the weld. Therefore, greater energy densities are needed to accomplish the welding process in these alloys, taking into account the fact that penetration becomes greater as the spot diameter decreases and power density increases (Katayama, 2013; Katayama, et al., 2009).

It is important to mention that the alloying elements composing the material have a remarkable influence in its thermal conductivity. Consequently, increasing the concentration of certain elements within the alloy to weld maybe improve its weldability. In the case of aluminium, several practical outcomes have demonstrated that by increasing the concentration of silicon, zinc or magnesium (Si, Zn, Mg) within the alloy a decrease of thermal conductivity is achieved, and therefore an improvement of weldability is also obtained. Furthermore, zinc and magnesium have a low boiling point and high vapour pressure, therefore the vapour recoil force becomes greater as the quantities of the alloying materials increase (Katayama, 2013; Katayama, et al., 2009).

Appendix 6.2. Reflectivity

This parameter is one of the most important ones in our case due to the high reflectivity given by aluminium alloys represents a problem when accomplishing a laser welding process, since it entails a low absorption of the energy provided by the laser beam (Katayama, 2013).

The absorption of the laser beam depends on its wavelength, reaching a greatest level as the wavelength of the input laser beam decreases. According to this criterion, the main types of laser beam may be ranked by its increasing wavelength (worse absorption) as follows (Katayama, 2013):

- High power diode laser (HPDL): 808 nm of wavelength.
- Nd:YAG: 1064 nm of wavelength.
- CO2: 10.640 nm of wavelength.

Furthermore, reflectivity is determined by the state presented by the surface to be welded. Accordingly, it is remarkable to clarify that factors as roughness, oxidation or pollutant presence have an important influence. In order to improve absorption, there exist surface treatments such as sandblasting or dark coating application which have resulted to decrease the reflectivity of these materials, as well as laser texturisation treatments (Katayama, 2013).

These techniques to reduce the reflectivity of aluminium alloys by preparing the surface involved, result to be much more effective in conduction welding processes than in keyhole mode, since the keyhole formation entails a greater absorption of the energy by repeated reflections within it (Katayama, 2013).

Appendix 6.3. Viscosity

This factor is determining when talking about the stability of the weld pool; the greater is the viscosity of the melt material within it the less expansion it suffers. The low viscosity of aluminium has been looked to be increased without success since it is unknown how to modify this factor (Katayama, 2013).

Appendix 7. Laser Welding for Pure Aluminium and Alloys

In Section 5 of the report, additional information about the welding modes has been presented. Hereunder a detailed explanation of the transition of the two main welding modes can be found. It exists a third welding mode that it is between the two mentioned before called transition mode. This regime generates welds with some features of the keyhole welding and some of the conduction mode. It could be supposed that the welding mode is defined exclusively by the energy density of the laser beam, however other factors are responsible for the corresponding regime. For instance, the welding speed or the beam diameter (Katayama, 2013).

Sometimes, is not easy to distinguish the welding mode developed when accomplishing the process. Generally the majority of times the welding mode is selected however, other times it just goes to transition without noticing. Consequently, there are a few methods that allow the detection of the transition between keyhole and conduction. These techniques are required because there are some parameters that induce this change. For instance, the laser beam defocusing is one of those, because the size of the welding or laser spot is increased lowering the energy density of the laser beam (Katayama, 2013).

One of the first techniques is about the study of the phenomenon mentioned before, laser defocusing. This is about the distance between the workpiece and the laser focus, originally this distance was taken only until +10 mm. Nevertheless, when using a defocusing of +100 mm the weld can be developed with a transition from keyhole to conduction. Combining it with lower cooling rates could increase the properties of the weld bead specifically for aluminium alloys. Another function of the defocused laser beam is that deep welds using high power lasers can be done with the conduction mode, avoiding some of the keyhole defects (Katayama, 2013).

Another way of detecting the transition between the two regimes is to observe the plasma plume. It is generated because the keyhole mode produces a higher evaporation rate of the material than the conduction mode. The study made at the literature established that the most used aluminium alloys are the 5000 series, proving the proper weldability they have (Katayama, 2013).

Appendix 7.1. Aluminium Defects.

In Section 5.2 of the report, a review of the main defects of aluminium laser welding is done. It focuses on the main defects of this type of material, that do not defer that much from the usual defects of the rest of the materials when the laser welding technique is used. The main defects suffered on an aluminium laser welding are the four already mention at Section 5.2, only two of them were explained in order to avoid repetition with Section 2.3. Despite this fact here below, an explanation of the other two defects can be found focused on the aluminium material.

In the case of an aluminium alloy being welded with pulsed laser welding, hot cracking is the mean defect. Therefore, the particular pulsed parameters should be adjusted to avoid this defect. Working with continuous wave laser has different preventions, especially checking the type of filler material used to avoid solidification cracking. Generally, the 5XXX alloys don’t have this problem if they are welded autogenously (Pastor, et al., 1999).

Continuing with the underfilling defect, it is higher at the keyhole mode especially at the unstable stage with negative defocusing. Underfilling comes lower when the keyhole becomes stable, and even lower when positive defocusing is used. Underfill is a common defect at aluminium alloy laser welding however, sharp shapes and notches are avoided. Therefore, the mechanical properties are not affected that much (Zhao & Debroy, 2001).

Focusing on the interaction between the laser beam and the melted metal, the defocusing of the laser beam can affect the weld pool quality. At the positive defocusing the focal point is located above the surface meaning that at the interaction surface is divergent. Therefore, the liquid metal is being depressed meaning that this one moves away from the interaction point, limiting the size of the weld pool. Working with negative defocusing the focal point is below the interaction surface meaning that the laser beam has a convergent geometry. The flow of the weld metal moves the material of the bottom part, letting the next surface being exposed to the laser. This produces higher keyhole depth and a larger weld pool. It should be mentioned that the defocusing affects the underfill formation. Using the actual techniques and working with aluminium alloys the bottom underfill does not happen. Focusing at the top underfill, it is produced by the expulsion of the melted material. Essentially, if the pressure balance is broken some air can open a conduit at the bottom weld area, carrying some liquid material. Taking into account that the laser beam is always moving forward, if the melted metal is not able to fill that space the underfill happens (Pastor, et al., 1999).