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Aweldability Study of AlMg0,7Si Aluminum Alloy by TIG, FSW, and LBW Processes

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Abstract - *The increasing use of aluminum alloys in structural and machine constructions is due to the good relationships between their mechanical properties and the processing capacity by various manufacturing processes. In terms of the weldability of these alloys, development continues to be decisive in the selection and optimization of welding processes.*

For this research, were compared three aluminum welding processes with origin in different energy sources: -electrical arc, TIG;- laser radiation, LBW;- mechanical energy with friction, FSW. The connections were made in butt joints of AIMg0,7Si-T6 bars, whereas thickness is 3 and 6 mm, which are typical in many welded constructions.

To make a better analysis of the experimental results, it was used a systematic disposition of results either of resistance as well as the hardness in the weld joints. This gives the ability to conclude analyses related to the true behavior of welded connections. Whereas σ-εbehavior gives you an idea of your endurance performance, the hardness distribution, by mapping, allows you to define the limits of HAZ and microstructural distributions.

The juxtaposition of the values calculated by the Eurocode with those obtained experimentally is a good indication for evaluating what is used in the project.

Keywords - *aluminum, Eurocode, hardness, strength, TIG, LBW, and FSW wildings.*

I. INTRODUCTION

The mechanical properties of aluminum alloys, weight and strength in particular, as well as the manufacturing processes available and the quality of the parts obtained, increase applicability in all sectors of production and construction.

The additive processes, which include welding, allow obtaining aluminum parts with the most complex shapes. In general, these parts have great advantages in the execution and rendering:

Aluminum alloys can show good weldability by various welding processes. Among the best welds are those obtained by TIG (Tungsten Inert Gas), laser (Laser Beam Welding – LBW), and FSW (Friction Stir Welding) [1], [2], [3]. These processes are the target of the study presented here.

II. MAIN CHARACTERISTICS OF TIG, LBW, AND FSW PROCESSES IN ALUMINUM WELDING

Each process has its advantages, although it also has some limitations. It is not an objective of this work to stooges them because it would be exhausting to mention the advantages of each one and then make inter-process comparisons. However, there are some advantages that are due to the characteristics of each process and, some of these will be presented below.

The TIG process (Tungsten Inert Gas or GTAW - Gas Tungsten Arc Welding) has its own functional characteristics, which makes it one of the main one's today. The numerous advantages of this process have been widely disseminated [4], [5]. It uses a non-consumable tungsten electrode and an inert gas (usually argon) to promote electric arc and gaseous protection. The fact that the electric arc is made between that electrode and the part allows it to be used with or without adding material.

Because it is an energetic and versatile process in the use of electric current, in a clean environment, it can do quality welding in most metals and their alloys, in connections of fine components, and in delicate parts.

The inexpensive and easy-to-maintain equipment, as well as the rapid adaptation to new cases, make this process a great alternative in industrial uses.

The LBW (Laser Beam Welding) process uses a high-density energy laser to weld at a high melting rate and low thermal distribution by the material of the parts, with or without additional material. The wide available range of power values, for use in the variants of continuous, pulsed, or by "laser spot"; in driving or keyhole modes; allows large alternatives, ranging from welding different materials and in a wide range of thicknesses, high welding speeds and great performance, great penetration which allows high precision with little deformation and distortion [6]. In addition, it remains in strong development, either laser sources or focus systems. But the equipment is still very expensive, requiring special care, and that requires mechanization equipment or robotization. The advantages of LBW welding, compared with conventional welding methods, are:

- No wear components due to contactless processing.
- Easily automatable and with high flexibility in terms of process and geometry.

- Resistant welding beads, good aesthetics, and high reliability.
- Allows working simultaneously on several workstations by means of beam diverters or splitters [6].

The FSW is a welding process without melting and without adding material, whereby the tool rotation generates heat by friction (Friction) and alteration of the plastic state of the metals, and these, when stirred, give rise to welding (Welding). It is one of the last inventions in the field of welding by TWI [7] because the process was patented (The Welding Institute) in 1991 and, for various reasons, has been the subject of great research.

The high level of reliability, both in terms of new possibilities and in the quality of the joint it provides, particularly in the welding of all aluminum alloys and different materials [3], [8], [9]. Being easy to implement, in which the main care and welding parameters are the speed of rotation (n) and advancement or welding speed (v_w) [10] [11]; the shape and dimensions of the tool, depending on the thickness and the materials to be welded.

The advantages of FSW welding, compared to conventional processes, are due to excellent mechanical properties, without porosity and low distortion. It produces welding beads with a good aesthetic appearance, completely cleaned and without creating harmful elements. The process can operate in any orientation because gravity has no influence on the quality of welding.

Due to the dynamics of the process to the plastic behavior on which the process is based, the internal distribution is different from the processes by fusion, either by asymmetry or by the affected areas, as can be seen in the diagrams in figure 1. In addition to the unaffected zone of the base metal, MB (A), and the zone affected by heat, HAZ (B), in both; there is the fusion zone ZF (C), in the scheme (a); whereas in FSW, there is the thermally mechanically affected zone, TMAZ (D) [xxx], and the stirred zone, SZ or nugget (E), in the scheme (b).

(a) (b)

Figure 1. Schemes of the affected zones in the fusion welding processes (a) and in the FSW (b). Source: own.

III. MATERIALS AND DESIGN

The aim of the study presented here is to analyze the behavior of joints in simple joints and compare the main processes of different origins in the weldability of an aluminum alloy used in mechanical construction.

A. Materials Used

Magnesium and silicon contents in AlMgSi aluminum alloys should be hardened by precipitation during the processes and treatments carried out during the first phase of its production. This results in a variety of alloys with good mechanical properties and good weldability. One of the most common is the Alloy AlMg0,7Si (AW-AlMg0.7Si - EN 573-2 / EN 1780-2; UNS A96063 (AISI 6063)), whose chemical composition is presented in table 1.

Table 1. Chemical composition ofAlMg0.7Si (Wt%).

Designation	Mg	Si	Fe	Cu	Mn	Cr	Zn	Ti	others
AlMg0,7Si	**0,45-0,9**	**0,2-0,6**	0,35	0,1	0,1	0,1	0,1	0,1	até 0,15

Source:[13]

Some of its main mechanical properties are presented in Table 2.

Table 2. Mechanical properties of AlMg0,7Si T6.

Properties	T_f (°C)	σ_c (MPa)	σ_r (MPa)	HV	ε (%)
Values	600 -655	160 – 210	195 – 255	83	9,8 - 10

Source: [14], [15].

The good mechanical properties of this alloy are due to its use in structural applications and due to the complex geometries of the sections of the profiles obtained and various accessories; used in construction and automotive, shipbuilding, offshore [16].

One of the objectives of this work was to allow the analysis and comparison of resistance values related to the connections in butt joints, as schemed in figure 2, through diagrams ofσ-ε.

B. Design Values

Traditionally, in this type of joints were not sizing of weld bead (NP EN 1993-4, 2008), i.e., full penetration is what ensures the strength range of the base material (which is a condition of the welding definition according to the IIW). This condition may not be verified and; however, the welded join can serve a certain application if resistance is not the fundamental condition. And there are many connections in these conditions.

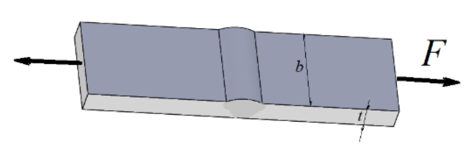


Figure 2. General scheme of the joints used in this work. Source: own.

The design resistance of an aluminum alloy weld bead is provided for in the Eurocode: EN 1999-1-1:2007, by the ratio (1), where $\sigma_{\perp Ed}$ and f_w is the normal tension, i.e., perpendicular to the plane of the welding bead and the characteristic strength of the additional metal. γ_{Mw} It is the partial factor for the resistance of cross-sections in tension to fracture.

$$\sigma_{\perp Ed} \leq \frac{f_w}{\gamma_{Mw}}, \quad (1)$$

For the alloy Al6063, with the values f_w=160 *MPa* and γ_{Mw}=1.25, is obtained $\sigma_{\perp Ed} \leq 128\ MPa$.
The design resistance in the heat-affected zone (HAZ), the normal stress, perpendicular to the referred plane but in the material in HAZ, is calculated in $\sigma_{haz,Ed}$ Thesame norm by the ratio (2), *where* $f_{u,haz}$ is the resistance to final traction in the heat-affected zone by.

$$\sigma_{haz,Ed} \leq \frac{f_{u,haz}}{\gamma_{Mw}}, \quad (2)$$

whose value of $f_{u,haz}$=110 *MPa*, then this $\sigma_{haz,Ed} \leq 88\ MPa$. In the case of welds without additional material, only this value is used.

IV. EXPERIMENTAL WORK

The experimental work consisted of the preparation and execution of the welds by the three processes, carried out under the same conditions, except with the adjacent particularities to each one. Samples were then cut and prepared, both for tensile testing and hardness measurements.

A. Preparation

Welds have been planned in order to always use this aluminum alloy in butt joints from bars with thickness of 6 mm (called A and B) and 3 mm (called C and D), the width of 60 mm and length 300 mm, so that, after welding, it would allow for cutting and making the specimens in equal conditions.

Welds can only be performed after gathering a set of generic care, which are the preparation of the joint, removal of oxides, and cleaning, according to requirements of EN 1090-3:2008. The preparation of the joint was based on the values found in the literature EN ISO 9692-1 and[17], [18]. The possible geometry of the joints and the values of the thicknesses (t), in which the clearance (r), the bead (f), and the angle of the chamfer (α)depend on the process; of course, in cases without additional material, the joints present with the tops of the bars in contact (r=0 in Fig.3 (a)).

Mechanical removal of the aluminum oxide layer (alumina, Al_2O_3) was done immediately before welding to prevent further formation [13].

a) TIG Welding

The execution of success TIG welding beads was only carried out after gathering a set of tasks: careful selection of the additional material, with the recommendations of EN 1090-1-1:2008 and with requirements of EN ISO 18273, cleaning and preparation of the joint, parameters, electrodes, nozzle, etc., with requirements of EN 1090-3:2008. The preparation of joints was based on the scheme of Fig. 3, with- r=1 mm, f=1mm and chamfersαfrom 60° to 100° to t=6 mm° (cases A and B);- r=1.5mm and without chamfer for thickness t=3 mm(cases C and D).

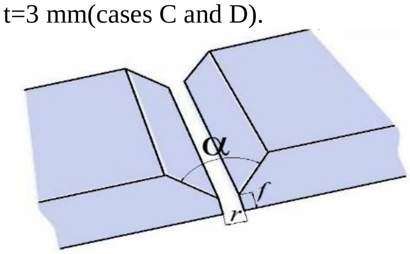


Figure 3. Generic geometry of the preparation of joints.
Source: own.

TIG welding was performed with Fronius Magic Wave 2200 Job equipment to get a thermal delivery value as low as possible. The optimization of the welding parameters was made: - use of alternating current and pure tungsten electrode (ISO 6848 WP class), corresponds to the green tip; -welding current intensity I_s = 150 and 135 A and welding speeds $v_w \approx$ 0.9 and 1.2 mm/s for the bars of the thickness of 6 and 3 mm, respectively. In welding to thicknesses of 3 mm, without addition material (case C), the parameters of each of the passes performed were: Is = 150 A and $v_w \approx$ 2.1 mm/s. Tungsten electrodes "theoretically non-consumable" are actually wearing elements. These and other types and diameters of electrodes for welder other metals, as well as the availability of nozzles of torches, should be considered in a competitiveness analysis with other processes.

The selection of the additional material to prevent hot cracking and obtain good mechanical properties was in the form of ER 5356 rods of diameter 2.4 mm.

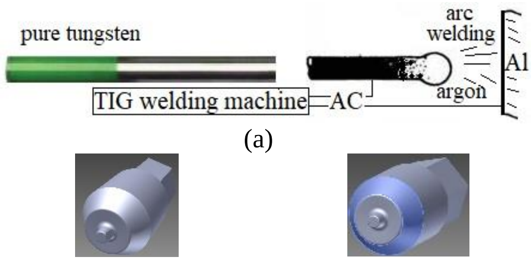
b) LBW Welding

The equipment available for the LBW process was a Trumpf TruDisk 6602 Laser, which is a source of disc laser beams, wavelength of 1030 nm, power up to 6.6 kW, beam quality of 8 mm. mrad, driven by fiber optics from 0.6 mm to the optical focusing device. The focusing distance is 72 mm at a point F=0 mm or another value that lies below or above the surface. It is assisted by a Kuka KRC2 robot; with linear feed or welding speed range, v_w=0.001 to 2 m/s [19], [20].
The equipment used does not yet have a device to enter additional material. The welding beads were executed without additional material with powers of 4 and 6 kW, focusing at F=1 mm depth, with and v_w = 0.0292 m/s.
There was no welding problem, although there is no experience in aluminum welding.

c) FSW Welding

The welds of the FSW process have been run on an a7.5 kW Bulin FU 321Muniversalmilling machine, working in vertical shaft mode. Support has been designed and constructed to allow to be adjusted on the machine table and rigidly fastened to the aluminum parts to be welded, figures 5 (c).

The tools were designed and developed in 3D CAD and executed on the available CNC machine. Geometrically, they are composed of the pin, shoulder, and fixing body, as shown in figure 4. In this work, it was chosen to use the simple geometry tools, with conical pins of 2.9 and 5.9 mm of extension to weld thicknesses of 3 and 6 mm, respectively. Their landings had diameters of 8 and 13 mm. The material used was AISI H13 steel and vacuum quenchedat 1100°C, with guaranteed hardness between 49 and 51 HRC.



(a)

(b) (c)

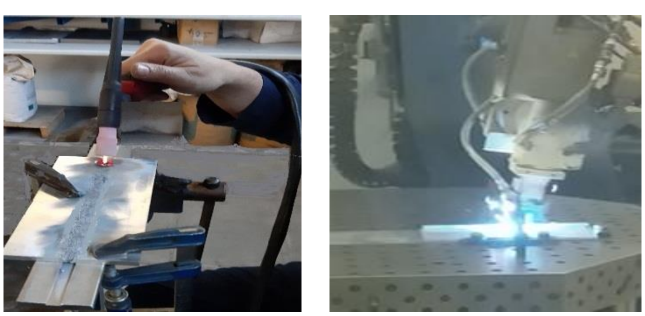
Figure 4. Wear elements related to (a) tungsten electrode for welding of aluminum alloys and their insertion in the process; (b) and (c) tools for FSW welding of 6 mm and 3 mm thick plates, respectively. Source: own.

Welding was achieved at the first attempt with a reasonable surface aspect. However, to achieve welding without internal defects, it was necessary to discharge parameters. Initially, the rotation velocities of n=800 rpm and traverse speed (or welding velocity) v_w= 25 mm/min in cases A, C, and D were initially adopted. Subsequently, the rotation speed was increased to n=1000 rpm in case B.

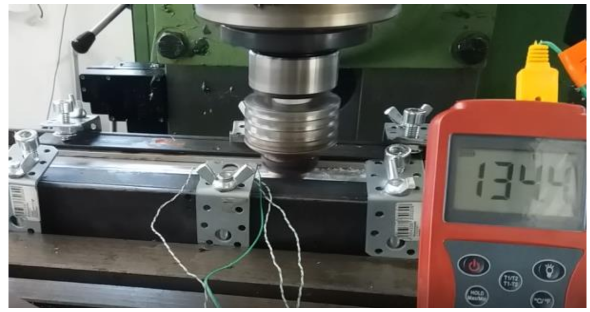
B. Execution of welds TIG

Initially, bevels were tried with a 60 and 90°, but the weld beads cracked longitudinally during cooling. The problem was solved when they were chamfered with α>90°.

On the surface of the cord, a black film was formed, as can be seen in Fig. 6 a), called "black smut", which is magnesium oxide. It is common in electrical arc processes with a 5XXX addition metal, and the ER 5356 is one of them because it contains magnesium. This anomaly has a bad surface appearance and is difficult to eliminate but does not affect the mechanical properties of the welding bead, not decreasing the strength of the connections [21].



(a) (b)



(c)

Figure 5. Photos of the equipment's used processes: - a) TIG, - b) LBW, - c) FSW.

Not wanting to choose another MA, based on Si (ER 4043, for example, because it does not promote such resistant connections), the solution has gone through the improvement of welding techniques, primarily in the proper regulation of protective gas and in the stick-out distance (less than 12.7 mm) [22] or with additional gas protection care.

Only in the event that the oxide is not removed before a resumption of an electric arc can it lead to solid inclusion inside the deposited metal [23] as with coated electrodes. Happened a case with breakage of the specimen at the beginning of the tensile test, which was found to be due to that effect.

a) LBW

Although without previous experience in laser aluminum welding, the welding beads were all made on the first attempt and with a surface appearance at least satisfactory, as can be seen in Fig. 6 b). However, and without disregard for surface quality, roughness is typical of fusion processes and out of the measurement field.

There were no spatter problems or draining the welds during processing. Subsequently, no porosity or other internal defects are found.

b) FSW

The welds made by the FSW process rarely have surface defects and present a good finish, fig. 6 c), which until it is possible to measure roughness. In its measurement, a Hommel Tester T1000 was used, and values of Ra (arithmetic average roughness), Rz (average roughness heights), and RSm (average roughness width) were chosen because they allow a better characteristic of roughness, both in-depth and in extension. Due to the good reproductivity of results, only3 measurements were made on each surface, as can be seen by standard deviations no.

Table 3. The surface finish of the weld bead surfaces.

	Ra	Rz	RSm
Average	0,423	2,687	0,034
Standard Deviation	0,027	0,033	0,006

The averages of roughness values: in height (Ra and Rz) and width (RSm); show a good finish of the surfaces of the welding beads obtained by FSW. And the number of roughness measurements in each case was sufficient, given the low values of their standard deviations.

Inwardly, the first FSW welds presented was the tunneling defect, but this was attenuated with the change in welding speed values, as it is advised in the bibliography, [24] for example.

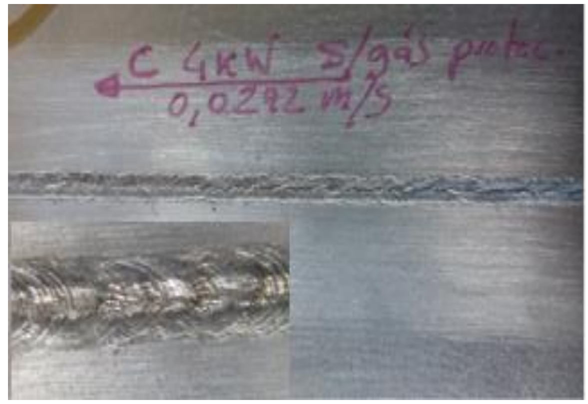
Another type of defect was the lack of total penetration due to the depth with which the tool enters the parts to be welded. In this work, rigid tools with pin with length based on some kinds of literature were designed and manufactured. However, it was not completely effective, with welds not completely covering the entire thickness, which was felt in the resistance results during the tensile tests.

C. Preparation and execution of tensile and hardness tests

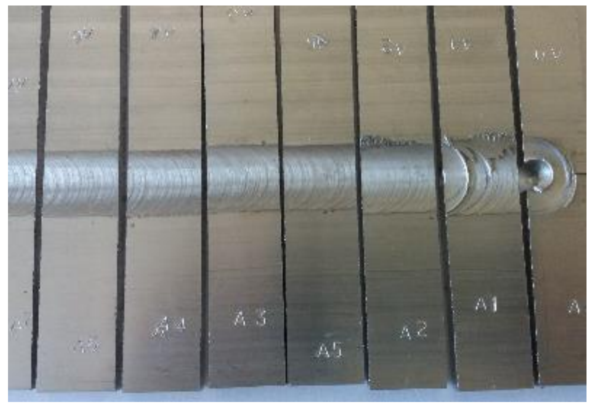
After the welded connections have been made, the production of the components, constituents of the specimens, has been carried out carefully. As required, numerical control (CNC) milling was used to ensure specimens with adequate geometry and precision.

Due to the nature of the plates extrusión working process is expected anisotropicbehavior[24]. Inthisstudy, the welding beads are conducted along the extrusión direction of aluminum plate sand. Thus, tensile tests are performed in the direction of the transversal. So, in comparison to the strong results, when there is a break of the specimen outside the bead zone, one can expect that there is a slight difference in comparison with the initial data,suchasthoseinTable2, for example.

(a)



(b)



(c)

Figure 6. Examples of Al6063 welds made by processes: - a) TIG; - b) LBW, - c) FSW; after cutting and before making the specimens, except in (b) showing a detail of the quality of the weld beads.

Due to the nature of the plates extrusión working process is expected an isotropic behavior[24].In this study, the welding beads are conducted along the extrusión direction of aluminum plates, and, thus, tensile tests are performed in the direction transversal. So, in comparison to the strong results, when there is a break of the specimen outside the bead zone, one can expect that there is a slight difference in comparison with the initial data, such as those in Table2, for example.

The traction testing machine used in this work was an Instrom 4206. The tests of the connections were carried out in their simplest form, obtaining the values of the evolution of force and displacement during the traction of the specimens. It was intended to compare the resistance of the connections, assuming that striction would not be significant.

V. ANALYSIS OF RESULTS

The results of the mechanical resistance of the welded joints produced are presented and compared systematically, allowing a more effective analysis.

A. Loading Curves

From the evolution of results F-ΔL the values of the stresses are obtained and hence the curves σ-ε, which allows the abstraction of the dimensions of the connections, the placement of all curves in the same graphic area leads to a more elucidative comparison. In all, a color systematization was used to facilitate this comparison, the tensile tests: - A and B, are to thickness 6 mm; - C and D are thickness 3 mm.They were not compared with the behavior of the metal without welding due to the small dimensions available to constitute the specimens in the transverse direction of extrusion.

From the curves σ-ε, relating TIG, the influence of the way welding was carried out is clearly distinguished.Thus, for the6 mm thickness, the maximum values of the stresses tend to be higher than those of3 mm thickness. In the case of 6 mm plates, the use of gaseous protection ensures a great homogeneity between all curves in the loading phase.

In LBW welds, the characteristic of the curves σ-ε clearly distinguishthe influence of the way they were made. For example, in the case of 6 mm thickness bar connections, the higher laser power leads to greater reproductivity, due to the slightest variation in results. The use of gaseous protection, in cases where the thickness was 6 mm, ensured a great homogeneity between all behavior curves of the loading phase.

On the other hand, in either the tests A (higher thickness plate and laser of lower power) and in C (lower thickness plate and without gaseous protection), a very significant difference between the strengths of the specimens is remarkable.

In the analysis of stress-strain curves related to FSW welds made, an effect related to the thicknesses of the original plates is clearly distinguished, with differences of up to 50%. However, they are the ones with the highest thickness that have the highest strength, all of which are higher than the base metal. It is also verified that between curves B (in red), they present higher stress values but lower deformations than A (in blue), although the thickness is equal. This is due to B curves being made later than the others but with slightly different speed values.

The explanation is due to the strain hardening increased, which is in accordance with [25], [26]. This conclusion is not developed since it is not part of the initial objectives of this study.

By the characteristics of the curves σ-ε, the influence of the way welding was made is clearly distinguished. For example, in the case of connections with a 6 mm of thickness, in LBW welding with gaseous protection (cases B), greater reproductivity of the results was ensured between all curves in

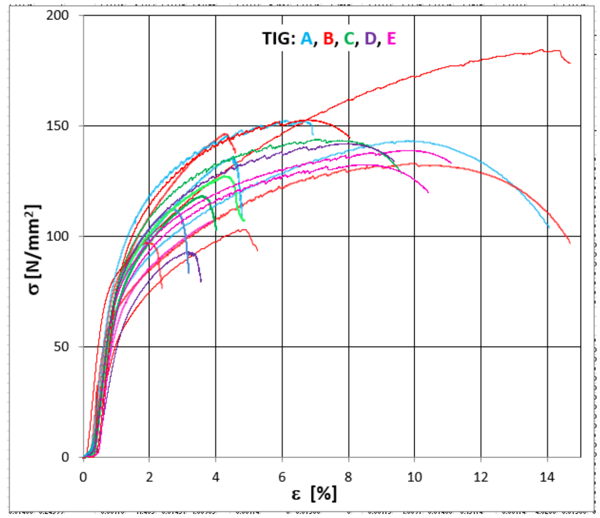


Figure 7. Comparison of experimental stress-strain results of TIG - Al6063.

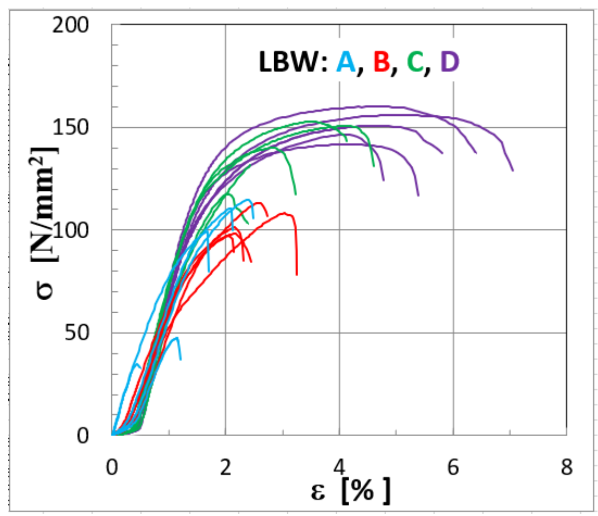


Figure 8. Comparison of the experimental results of strength - displacement and tension- formation of the LBW - Al6063.

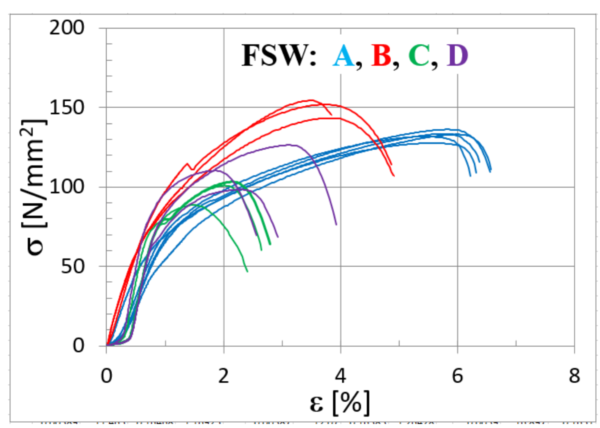


Figure 9. Comparison of experimental stress results - a strain of FSW.

The loading phase. On the other hand, in cases A (higher thickness and laser of lower power) and in cases C (smaller thickness and without gaseous protection), a significant difference between resistance behaviors is remarkable.

B. Comparison of design and experimental loading results

The comparison between values calculated by Eurocode and the maximum load values of the experimental results is shown in the bar chart in figure 10.

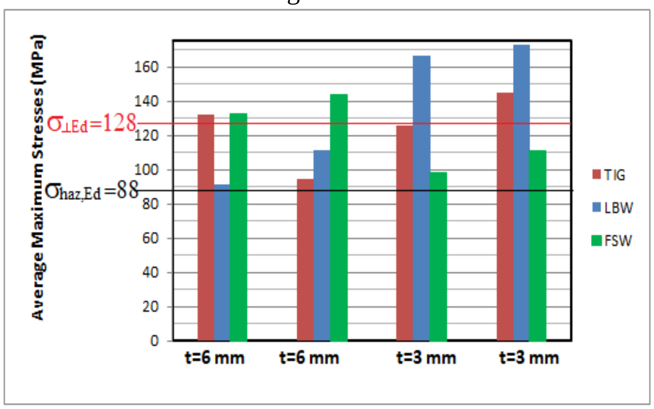


Figure 10. Comparison of the mean values of the maximum stresses of the experimental assays, in the case of thicknesses: - 6 mm - A and B; – 3 mm - C and D; overlap of design boundaries.

From the analysis of the results, it is verified that all welding carried out with the TIG process, without and with adding material, meets the criterion:$\sigma_{haz,Ed}$, but not everyone who uses MA meets the other criteria:$\sigma_{\perp Ed}$.

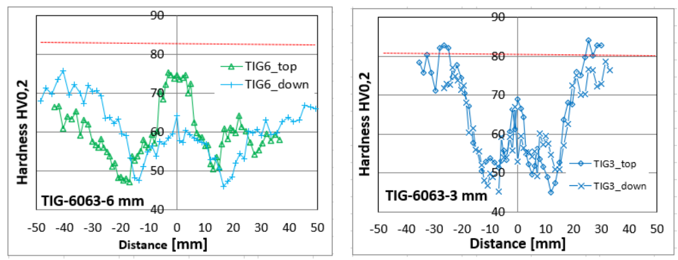
C. Analysis of hardness distribution through the joint

The evolution study of hardness along the distribution of affected zones allows the analysis of the influences of microstructural changes in the areas of molten metal and affected by heat, i.e., their measurement through the heat-affected areas.TIG welds have greater width differences between higher hardness distributions than at the bottom of the weld bead when compared to equivalents from other processes. This is due to lower energy and penetration capacity than in the case of LBW. In FSW, however, it is due to the nature of the process.

In this work, the biggest decreases in the hardness values are situated in the vicinity of the weld bead. The differences between maximum and minimum values are about: 38, 35, and 42% by TIG, LBW, and FSW processes, respectively. In the case of the FSW process, carried out with smaller welding speed (v_w), this decrease is in the range of values that are found in some bibliography [27], [28], for example. This decrease is justified by the heat input and the high density of grain boundaries in the stirred zone or Hall Petch effect [28].

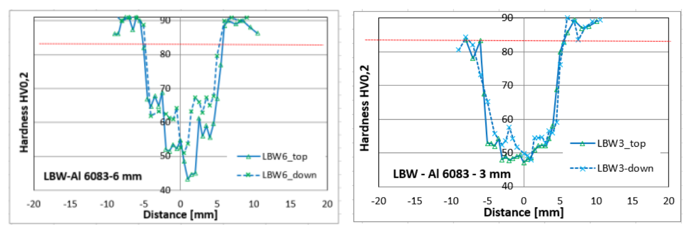
Chainarong et al. [29] concluded that the hardness value in the stir zone might be lower or higher than in the base metal, depending on the values of $v_w$if low or high, respectively. Thus, and although the beads have a good surface appearance and exemptions from internal defects have been achieved, it is concluded that the v_w values should be higher.

The extents of the hardness value distributions also allow you to draw good conclusions. By analyzing the graphs of figures 11, 12, and 13, between the fusion welds is the LBW process that presents less extensive ZTAs, which was expected to be due to the energy difference of the processes. Although FSW welds do not involve fusion, they have extensive ZTAs than LBW. They also present some asymmetry, and their lower value is not located in the center, as already verified in [26], [29], [30], due to the direction of rotation of the tool in relation to the feed, caused by the asymmetric flow of plastic material to one side, originating the "nugget", as schematized in 1 (b).



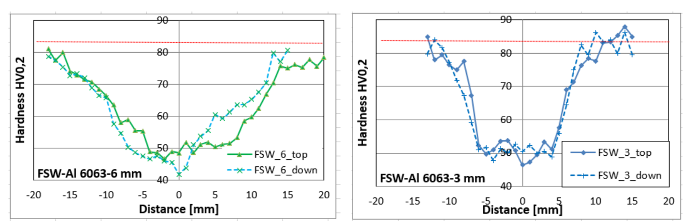
(a) (b)

Figure 11. Comparison of hardness results of TIG welds:-(a) without addition material (t= 6 mm);–(b) with addition material (t= 3 mm).



(a) (b)

Figure12. Comparison of hardness results of LBW weldswithout addition material: –(a) t= 6 mm; – (b) t= 3 mm.



(a) (b)

Figure 13. Comparison of hardness results of FSW weldswithout addition material: –(a) t= 6 mm; – (b) t= 3 mm.

A priori, it will be better to weld with smaller differences in hardness values and that their gradients are not high, which means smaller microstructural variations which means better behavior in terms of strength and toughness. In the cases of the present study, no distribution stands out in all distributions, which leads to the conclusion that there is no process that is better than the others.

VI. CONCLUSIONS

The first conclusions were already expected: - there are significant differences in the results of connections made by processes of a different nature, in this case between electric arc, friction and laser mainly because there are differences due to the use or not of addition material.

In a manual process, as in TIG, only one welder with extensive experience or who always welds the same type of material is able to weld well at first. But in a more energetic and automated process, it is almost immediate to welding another material.

Quality aluminum alloy welding requires the meeting of a number of precautions, most particularly in the TIG process with MA, which depends on multiple factors. These are related to the selection of MA and welding parameters, gas, as well as techniques related to metallurgical and operational weldability. LBW and FSW, mainly because they did not involve MA, are simpler to run.

In the comparison of resistance results, with each other and with the expected sizing and those available in the literature, one can reach the following conclusions:

The TIG process provides the values with the highest strength, but with greater dispersion.Inthe LBW process there wassomedispersion of results in cases where no protective gas was used. This process has better resistance in smaller thickness welds. In FSW, there was less dispersion, but parameter optimization can bring advantages, particularly tool rotation speed.

The analysis of the hardness distribution may reveal the microstructural changes due to the processes and the particularities of the way it was processed.

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