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STUDY OF WELDING FSW (FRICTION STIR WELDING) OF ALUMINUM ALLOY 2024-T3 AND ELECTROLYTIC COPPER

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Abstract. This paper presents results from an experimental study of the process of Friction Stir Welding (FSW) in non-ferrous metals such as Aluminum and Copper, and its alloys. The FSW technique can utilize a milling machine and a cylindrical tool with a specific pin for this purpose. This tool rotates at a certain speed and pressure in order to heat the metal, softening them in the region of the joint of two sheets, and thereby perform continuous welding in the solid state. To study the FSW technique, some specimens were produced and subjected to tensile test. Preliminary experimental results showed that, compared with literature results, they could still be improved. So, tests were again undertaken with the following remarks: (i) the use of FSW AA2024-T3 alloy Aluminum and electrolytic Copper with 99.9751% of purity that once welded and inspected, can be detected the presence of defects, (ii) the defects were found according to existing literature, (iii) the results were analyzed in the region of the welding. Thus, a broad idea of application of FSW technique is presented, highlighting that this technique already has numerous applications in the aerospace, aeronautical and naval industries. Furthermore, the technique presented herein has a cost-benefit very interesting and low environmental impact, which favors its use in the domestic industry.

Keywords: FSW, welding, solid state, pin tool, AA 2024-T3

1. INTRODUCTION

With the continuous development of new manufacturing technologies, the aerospace, marine, automotive and energy generation industries, among others, require new types of materials and often they look for innovative techniques for using these materials.

The welding processes based on fusion GMAW (Gas Metal Arc Welding) and GTAW (Gas Tungsten Arc Welding) have been widely used for welding nonferrous materials, mainly Aluminum and its alloys, in recent decades (Machado, 1996). These processes are well known, but they are still extremely costly. It is important to pay attention that the quality of the junction depends on the preparation of the joint to be welded. Special care during the welding process and the need for skilled labor means high cost to use these processes in industry. Furthermore, GTAW and GMAW require a powerful source of energy, since preheating can be of the order of 500°C, making the welding process even more expensive.

The search for new welding techniques that may reduce production costs, expand the types of materials used and, preferably, be a clean technology that does not cause major environmental impacts in terms of pollution or expense energy, has been the subject of studies of various research groups in the world.

A relatively new technique which has shown good results is the mixing-friction worldwide known as Friction Stir Welding – FSW. This technique was patented in 1991 by The Welding Institute (TWI) in England. This welding technique consists in the union of two similar or dissimilar materials by friction in the solid state, using a non-consumable pin tool. In this process, there is no fusion of the materials involved and the original characteristics of the materials are best preserved when compared with other welding processes.

The FSW process is particularly useful in the welding of large plates of Aluminum, which can not receive tempering treatment after welding (to recover the lost properties during the welding) due to its extensive size (Nascimento, 2010).

The welding process by FSW has been studied by experimental tests that assess the structural integrity (static strength, fatigue life, fracture toughness, crack propagation and mechanical traction) and also by computer simulations which can predict some of these characteristics. Some of the pioneering works carried out for Aluminum alloys are: software development based on knowledge of welding systems that have voids and cracks (Napolitano ***et al.***, 1992), study of an increase in welding speed (Dawes, 1995), welding study from both sides of a joint at once (Knipström, 1995), performance evaluation of Aluminum alloy of 6000 series by fatigue (Haagensen ***et al.***, 1995, Dawes, 1996), and production of Aluminum profiles by FSW (Midling, 1996). The FSW process is already in commercial use and has been found to be a robust solution, parameter tolerant technique, which has much to offer in Aluminum welding (Christner and Sylva, 1996). Among numerous types of existing junctions it can be shown the main ones in Fig. 1.

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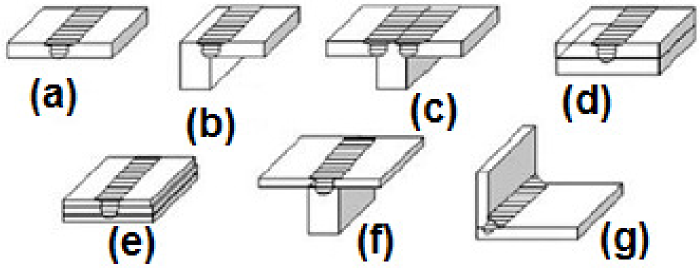

Figure 1. FSW joint configurations: (a) top simple, (b) top edge, (c) top T, (d) lap joint, (e) multiple lap joint, (f) lap joint T and (g) fillet joint (Mishra, 2005)

In the aerospace industry, Boeing used FSW in the launch vehicles Delta II and Delta IV. NASA has been using FSW at some external tank of the Space Shuttles, such as ARES I, Falcon I and Falcon 9 – the latter is illustrated in Figure 2.

Figure 2. Rocket engine fabricated by FSW

2. EXPERIMENTAL DESCRIPTION

The FSW welding technique and the materials used in the specimens will be described in this section, taking into account the choice of the most appropriate tool pin, the use of copper-joint (backing) and its corresponding material, details of the welding procedure, and their respective parameters.

2.1 Pin Tool and the Equipment

After preliminary tests with some types of pin-tool made of carbon steel SAE 1045, SAE 4140 and SAE 4130, it was found that the use of those with the shoulder in stainless steel AISI 304 and the removable pin in pure Tungsten showed less wear of parts with good experimental results, as it will be seen in a proper time. The geometry of the pin tool should be tailored to each type of joint and material. Figure 3 shows the pin used for welding of the specimens of this work, which was selected from 4 different types of pins used in these preliminary tests. The shapes of the pins tested were selected from the literature.

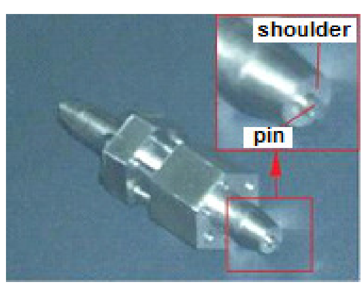

Figure 3. Pin tool used in the welding of the specimens on top joints

2.2 Mechine tool and accessories

To perform the welding it was used a milling machine of precision type American Bridgeport series I model M-105H with AC motor of 1.5 HP at nominal 1200 RPM. The final rotation can vary from 275 to 4550 RPM, but with

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considerable loss of power above 2000 RPM. This milling machine is equipped with automatic position table of 762 mm x 914 mm and with adjustable 1067 mm of headroom. Among the accessories it is important to highlight robust jaws used to fix the specimens. In Figure 4 one can see a schematic illustration showing the equipment used and the main part functions as the FSW welding is performed.

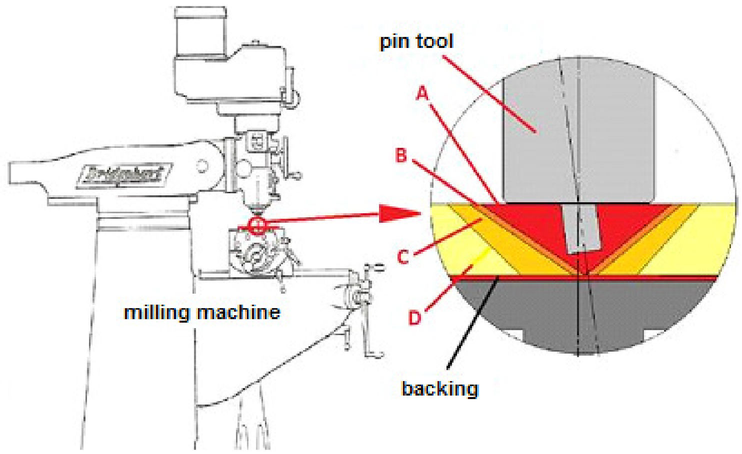

Figure 4. Scheme of the milling machine used for FSW welding with cross-section detail of a top joint

The specific regions of the FSW process, according to Fig. 4 are:

A – Mixing zone which corresponds to the region in which the pin has passed by it during welding, and thus it is highly deformed. Its grain size is well below that of the original material, and it is common to have rings not well stabilized in the cross section of the joint.

B – The thermo-mechanically affected zone (TMZA) is around the mixing zone. Here, the material deformation and the temperatures are lower and the effect on the microstructure of the weld is also less, unlike the mixing zone where the microstructure is derived from the original material.

C – The heat affected zone (HAZ) is characterized by being subjected to a thermal process without having been deformed during welding. Temperatures are below when compared with the TMZA, but still has a significant effect, because the microstructure is thermally unstable. It is usually in the HAZ where the failure occurs (Nascimento, 2010).

D – Flow arm zone, in the upper surface of solder, is composed of material that was drawn by the shoulder from the front joint, and deposited at the posterior part (Nascimento, 2010).

The FSW welding technique provides better results in terms of strength, ductility, fatigue, and fracture toughness when compared with other techniques. However, there is no consensus regarding corrosion in the FSW welding.

The FSW welding uses a cylindrical tool consisting of a shoulder and a pin, which is set in rotation and has a function of heating and mixing the two parts of the edges to be welded, thus creating the junction of the parts. The tool has a portion that does not penetrate the material to be welded, but it turns on it, thereby generating friction and heat to plasticize the material to be joined. The characteristics of the process and the tool used in order to obtain welds with structural efficiency are very important in this process (Mishra and Ma, 2005). Figure 5 illustrates the friction in a FSW welding process by its phases.

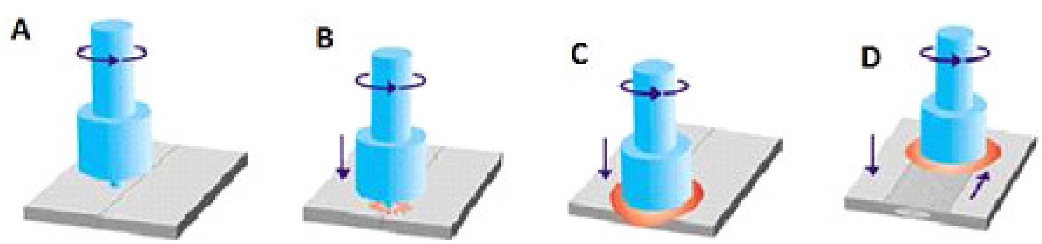

Figure 5. The friction process: (A) preparing to dive the tool, (B) diving the pin into the material, (C) applying force to the shoulder, and (D) performing translation in the welding line

In this process, the tool moves continuously along the junction always under the influence of a vertical force, shown in Figure 5b. The rotational and translational movements generate heat which provides a localized plastic deformation as seen in Figure 5c. The heat softens the material in the vicinity of the tool without melting it. With the displacement

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and rotation of the tool, the material is moved from the front to the back of the pin, promoting the binding of the two plates and forming the welded joint, as shown in Figure 5d.

The bonding conditions for FSW are complex depending on the alloy to be welded, welding parameters, geometry of the tool, etc. The prior simulation, both analytical and numerical, is important to understand the heat generation in the contact surface. The CFD (Computational Fluid Mechanics) approach is being implemented by using commercial computational packages such as FLUENT. Figure 6 shows an example of a numerical simulation using FLUENT, where one can observe the energy distribution during the welding process by FSW.

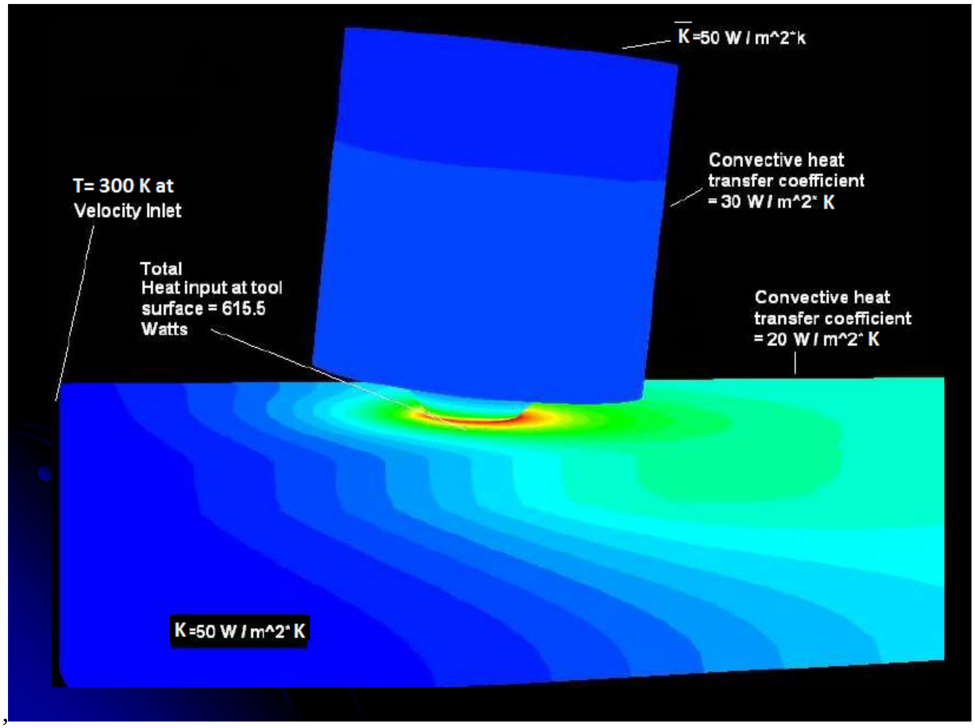

Figure 6. Illustration of the use of FLUENT computational package to simulate the FSW process.

It is well known that some metal alloys are difficult to achieve fusion welding, for example, the Aluminum alloy 2XXX and 7XXX series, widely used in aircraft structures. However, the FSW welding process can provide the union of these alloys in the solid phase. Mendez (2000) reports that the FSW welding strength is 30% to 50% higher than those processes with welding arc, and that the fatigue life is comparable to parts riveted. A major advantage of this type of welding when compared with others, is the possibility of replacing in the material the rivets by a direct FSW welding. In addition, there is an increase of the quality of some mechanical parameters, such as mechanical traction, being possible to reduce the weight of the material due to replacement of the rivets by the FSW welding. The FSW technique can be applied to various types of joints, and it is not required any preparation on the surfaces of the plates to be joined (Mishra, 2005).

Cruz and Moura Neto (2009) present a variety of types of materials and alloys, especially Aluminum, and conditions of the FSW (in production, development, and research) (see Table 1). According to SAE MAS -QQ-A-250/4A (1988) the chemical composition of the Aluminum alloy AA 2024-XX should observe the imposed range in Table 1, where the Magnesium content is a limiting factor for the fusion welding process.

Table 1. Weight percentage of some alloys of high resistance, as found in Cruz and Moura Neto (2009).

Cu	Mg	Si	Mn	Fe	Zn	Cr	Ti
3.8 – 4.9	1.2 – 1.8	0.0 – 0.5	0.30 – 0.90	0.0 – 0.50	0.0 – 0.25	0.0 – 0.10	0.0 – 0.15

The alloy Al-Si-Mg, treated by heating, presents loss of mechanical properties as shown in Table 2 when they are welded by fusion process. In this case, there occurs dissolution of the precipitates in the HAZ, generating a region with characteristics of solubilized material. Adjacent to this area, there is another place where happened a coarsening of precipitates. In both areas there is a loss of mechanical properties with greater intensity in the region solubilized.

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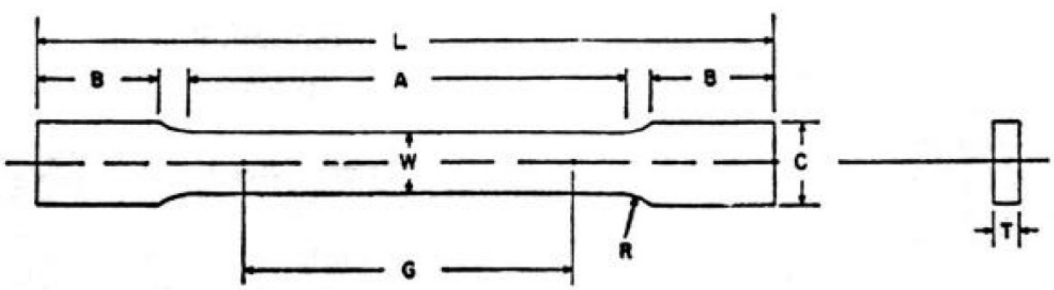
Table 2. Properties of the alloy 2024 under various treatments (Boyer, 1984)

Treatment	Strength Sr (Mpa)	Displacement A % in 50 mm	Hardness Brinnel HB
0	185	20	47
T3	485	18	120
T36	495	13	130
T4, T351	470	20	120

3. TESTS

In the present study, the specimens were produced from an Aluminum alloy AA 2024 T3 and from electrolytic Copper (99.97510%). These samples were made up in accordance with Figure 7, and subjected to visual testing, liquid penetrant and mechanical traction, as shown in Table 3. These tests were conducted with samples of pure base metal and welded by FSW, respectively.



	Dimensions, mm
Nominal Width	Standard Specimens Sheet-Type 12.5 mm
G—Gage length (Notes 1 and 2)	50.0 ± 0.1
W—Width (Notes 3 and 4)	12.5 ± 0.2
T— Thickness (Note 5)	3,0
R— Radius of fillet, min (Note 6)	12.5
L— Overall length, min (Notes 2 and 7)	200
A— Length of reduced section, min	57
B— Length of grip section, min (Note 8)	50
C— Width of grip section, approximate (Notes 4 and 9)	20

Figure 7. Shape and dimensions of the specimens with rectangular cross section (ASTM, 2001)

Table 3. Materials and thickness as used in the tests

Material	**Thickness (mm)**	**Visual test**		**Liquid penetrant test**		**Tensile tests**	
		Metal base	***FSW***	Metal base	***FSW***	Metal base	***FSW***
Alloy AA 2024 T3	3.0 ± 0.1	X	X	X	X		X
Electrolytic Copper	3.0 ± 0.1	X	X			X	X

The visual examination consists of the material surface analysis with naked eye, so as to detect discontinuities in the surface. The liquid penetrant test is also used to detect discontinuities with minimum dimensions, since it uses a liquid which penetrates into existing small cavities in the material. The technique reveals discontinuities in the surface of the material using a red liquid penetrant which contrasts with a white powder sprinkled, after removal of excess liquid. Finally, the tensile test allows an analysis of the mechanical properties of the material.

The mechanical tensile tests were performed at the Mechanical Testing Laboratory in the Division of Materials (AMR), of the Institute of Aeronautics and Space (IAE), of the Department of Aerospace Science and Technology (DCTA).

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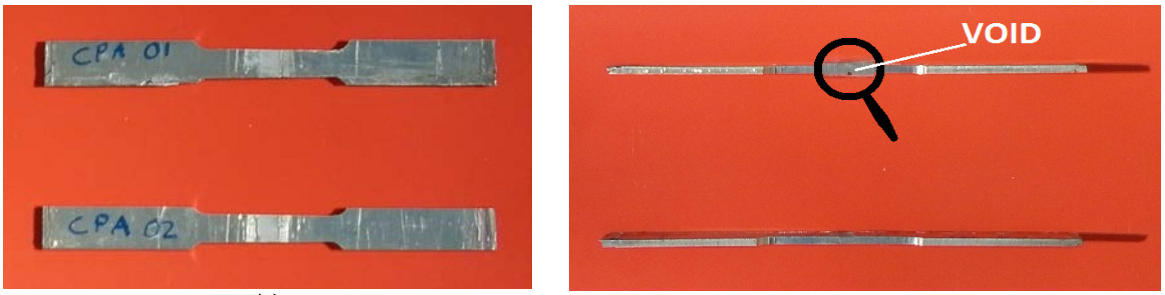
3.1 Results

The specimens were produced of Aluminum alloy AA 2024-T3 and electrolytic Copper. Figures 8 and 11 show images of the specimens of the AA 2024 T3 alloy and electrolytic Copper, respectively, obtained with FSW technique.

From Figure 8 it can be seen that the joint obtained by FSW was satisfactory in the face and on the root of the weld. In Figure 8 (b), the first specimen (from top to bottom) shows a dark point which indicates the presence of a void close to the root of the weld. Rosato Jr. (2003) observed the same effect and explained it as being due to insufficient forging pressure exerted by the tool.

Figure 9 shows the results of the mechanical tensile tests.



(a) **(b)**

Figure 8. Images of the specimens of alloy AA 2024 T3, (a) front view (b) lateral view

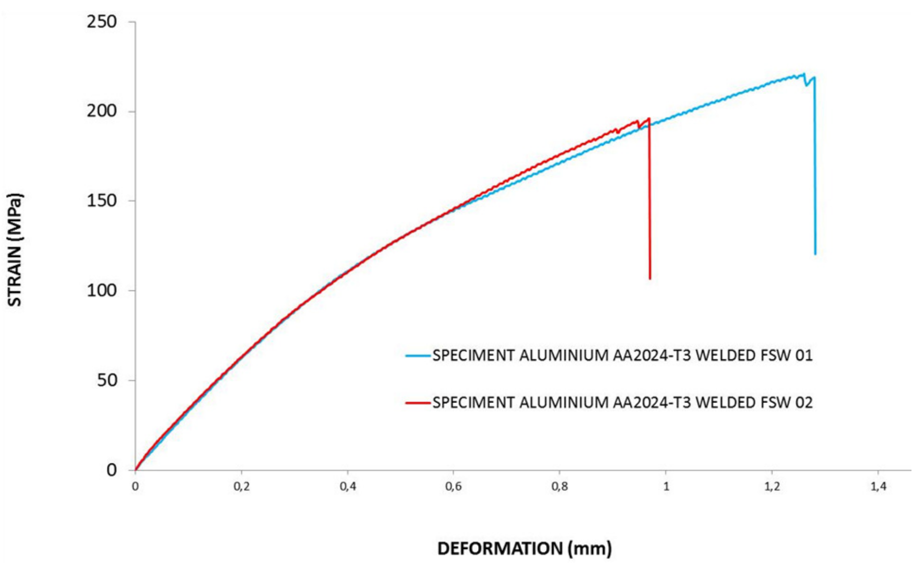


Figure 9. Results from mechanical tensile tests with the specimens of alloy AA 2024 T3

The numerical simulation can predict the formation of the void as it can map the trace of material separation that can occur between the specimen and the tool. Figure 10 shows the void forming on the lower side of the tool advance line, near the tensioned side of the specimen in contact with the pin. This is due to incomplete deposition of the material deformed plastically.

Figure 11 shows the specimens made of electrolytic Copper. The first from base metal, and the second and the third obtained with FSW technique. Figure 11 (b) illustrates the same specimens from lateral view. Figure 11 shows that the visual test was satisfactory but still other tests were performed by liquid penetrant without detection of surface discontinuities.

The absence of internal defects was confirmed by tensile test shown in Figure 12. Observing the stress-strain curves in Figure 12, with different specimens of copper, it is possible to conclude that the slope of the line tends to be parallel to the axis of application of the load as it moves away from the axis of deformation. The slope or modulus increases and it is directly proportional to the increase of interatomic binding energy (Callister, 2000).

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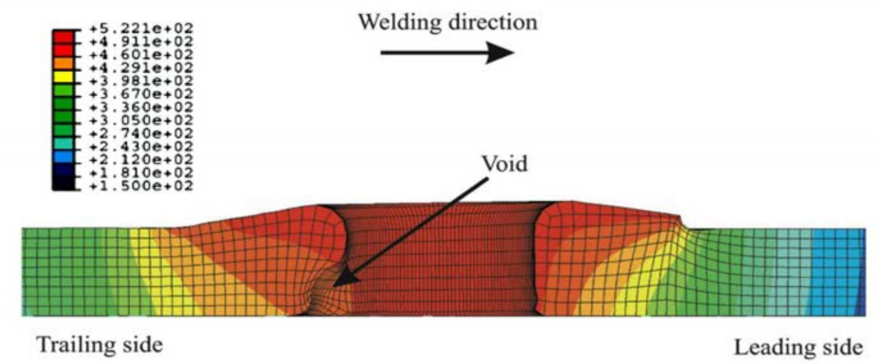
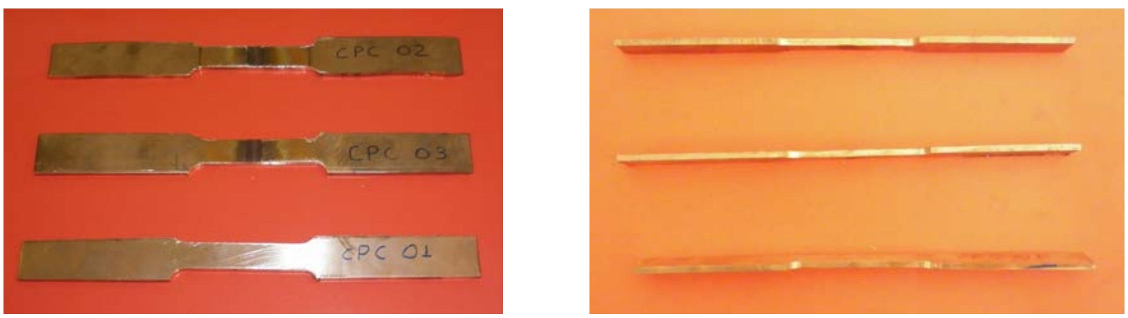


Figure 10. Void formation as it can be seen in the numerical simulation



(a) (b)

Figure 11. Images of the specimens made from electrolytic Copper (a) front view and (b) lateral view.

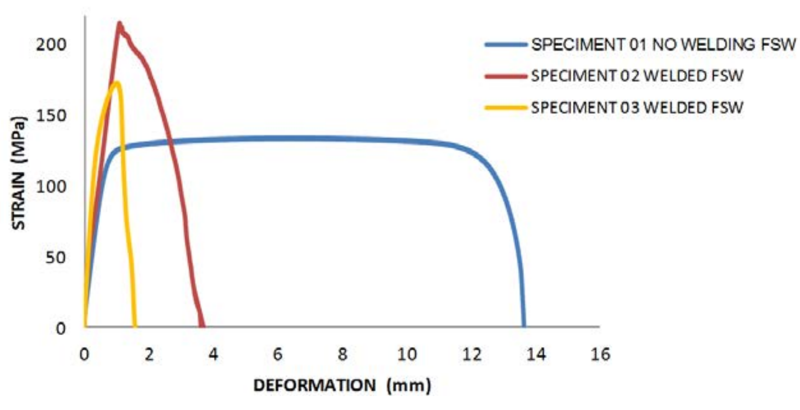


Figure 12. Results from mechanical tensile tests with specimens of electrolytic Copper.

One first observation of the graphic is that the samples welded by FSW had higher mechanical strength than the base metal sample (37% and 72%). This considerable increase in the tensile strength of Copper was due to forging and consequently to the grain refining in the mixing zone. Another important observation is that the ductility was greatly decreased.

4. CONCLUSION

The efficiency of the welded joints is of the order of 0.45 compared to the base metal aluminum and 1.6 for copper, with significant loss of ductility. It is also important to note that the good electrical conductivity of these materials is linked to the absence of discontinuities in the junction.

Currently joints of this Aluminum alloy is widely made by riveting, because of limited using of fusion welding which, when carried out, the mechanical results are negligible. As for copper, due to high energy demand for fusion welding, it can be seen their excellent results demonstrated in tests when occurred increase in mechanical strength of the welded material.

There is no doubt that the future application of these joints is very promising. Although Aluminum alloy present a joint with low efficiency when made by friction-mixing process (FSW), it already represents a major breakthrough just because the fact that allow a welding joint. However, the void observed is the limiting factor of the mechanical properties of the joint. The study of defects and their prevention is of great importance to the success of the process. However the adoption, even if restricted, of this process in the industry can improve quality making it competitive and thus promoting the consolidation in the market.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

ASTM -E8M, 2008, “Standard Test Method for Tension Testing of Metallic Materials.” ASTM International.
Boyer, H. E., 1984, ***Metals Handbook***, ASM International Publication.
Callister, W. D., 2010, ***Materials Science and Engineering – an introduction***” 8th edition - (USA) The university of Utah – Department of metallurgical engineering.
Christner, B. K., Sylva, G.D., 1996, “Friction Stir Welding Development for Aerospace Applications”, Proceedings of Conference ICAWT 96; Columbus, USA, pg. 359-368.
Cruz, M. F., Moura Neto, C., 2009, “Friction Stir Welding – Review: Potencial de Aplicação na Indústria Aeroespacial”, XI Simpósio de Aplicações Operacionais em Áreas de Defesa, DCTA, São José dos Campos, SP, Brasil.
Dawes, C., 1995, “Friction Stir Joining of Aluminium Alloys”, TWI Bulletin 6, pg. 124-127.
Dawes, C. J., 1996, “Seam Welding Aluminium Sheet and Plate Using the Friction Stir Welding Process”, In: 6th International Symposium, JWS, Nagoya.
Haagensen, P. J., Midling, O.T., Ranes M., 1995, “Fatigue Performance of Friction Stir Butt Welds in a 6000 Series Aluminum Alloy”, Computational Mechanics Publications (USA), pp 225-237.
Knipstrom, K. E., 1995, “Welding Method for Aluminium”, Svetsaren; Vol. 50, 185 , pg 5-6.
Machado, I. G., 1996, “Soldagem e Técnicas Conexas: Processos”, Porto Alegre, Brasil, 477 p.
Mendez, P. F., 2000, “New Trends in Welding in the Aeronautic Industry”, Massachuts Institute of Technology, USA, Cambridge-MA.
Midling, O. T., 1996, “Production of Wide Aluminium Profiles by Solid-state Friction Stir Welding”, 6th International Conf. on Extrusion Technology; Chicago; May.
Mishra, R. S., Ma, Z. Y., 2007, “Friction Stir Welding and Processing”, Edited by R.S. Mishra and M.W. Mahoney, Materials Science and Engineering (R50), p. 1-78.
Napolitano, R., Kulluk, H., Nagurka, M., Martukanitz, R., Dickerson, P., 1992, “Development of Knowledge-Based Systems for Aluminum Welding,” AWS Welding Journal, Vol. 71, No. 12, pp. 43-47.
Nascimento, I. C. F., 2010, “Estudo Numérico do Comportamento Estrutural em Pós-Flambagem de Painéis Aeronáuticos Rebitados e Fabricados por Tecnologia FSW”, Trabalho de Graduação, Instituto Tecnológico de Aeronáutica, DCTA, São José dos Campos, SP, Brasil.
Nandan, R., 2008, “Recent Advances in Friction Stir Welding – Process, Weldment, Structure and Properties” 2008 Department of Materials Science and Engineering Pennsylvania State University, University Park, PA 16802, USA Department of Materials Science and Metallurgy University of Cambridge, Cambridge CB2 3QZ, U.K.
Thomas, W. M., Nicholas, E. D., Needham, J. C., Murch, M. G., Temple-smith, P., Dawes, C. J., 1995. “Friction Stir Butt Welding,” International Patent Application No. PCT/GB92/02203; GB Patent Application No. 9125978.8, 1991; US Patent No.5460317.
Wittmann, R. J., 2010, “Estudos de Integridade Estrutural em Juntas de AA2024 unidas por Friction Stir Welding”, Instituto Tecnológico de Aeronáutica, DCTA, São José dos Campos, SP, Brasil.

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