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FRICTION STIR WELDING DEVELOPMENT OF ALUMINIUM ALLOYS FOR STRUCTURAL CONNECTIONS

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Since its development in '90, Friction Stir Welding (FSW) had known an important growth, especially for the hard to weld aluminium alloys. For these FSW has been shown to produce welds of high quality with no defects, reduced cost and lower environmental impact when compared to traditional fusion welding. The process parameters influence on the connection formation is related. An experimental program realized by HZG of FSW, applied on two aluminium alloys recommended to be used in the field of civil engineering is presented. Detailed characterisations are presented aiming to emphasize the performance of the process for the analysed alloys.

Key words: Friction Stir Welding, aluminium alloy, lower environmental impact, connections, residual stress

1. INTRODUCTION

Friction Stir Welding (FSW) is a solid-state welding process created and patented by The Welding Institute (TWI) in 1991. It is a relatively novel joining technology, which has caught the interest of many industrial sectors, including automotive, aeronautic and transportation due to its many advantages and clear industrial potential. The process adds new possibilities within component design and allows more economical and environmentally efficient use of materials [1–4].

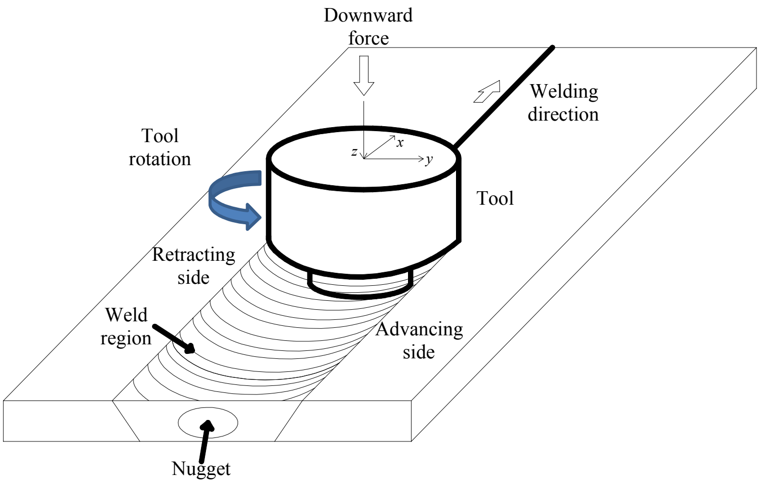


Fig. 1 – Schematic of the friction stir welding process.

In FSW (Fig. 1) a cylindrical, shouldered tool with a profiled probe is rotated and slowly plunged into the joint line between two pieces of sheet or plate material, which are butted together. Frictional heat is generated between the wear resistant welding tool and the material of the work pieces [5]. The heat causes the materials to soften, without reaching melting point (typically in the range of 70–85% of the melting temperature), and allows the pin to traverse along the joint. As the tool moves along, the material is plasticized by the frictional heat at the front of the rotating pin and transported to the back. The usual connections that can be realized using FSW are presented in Fig. 2.

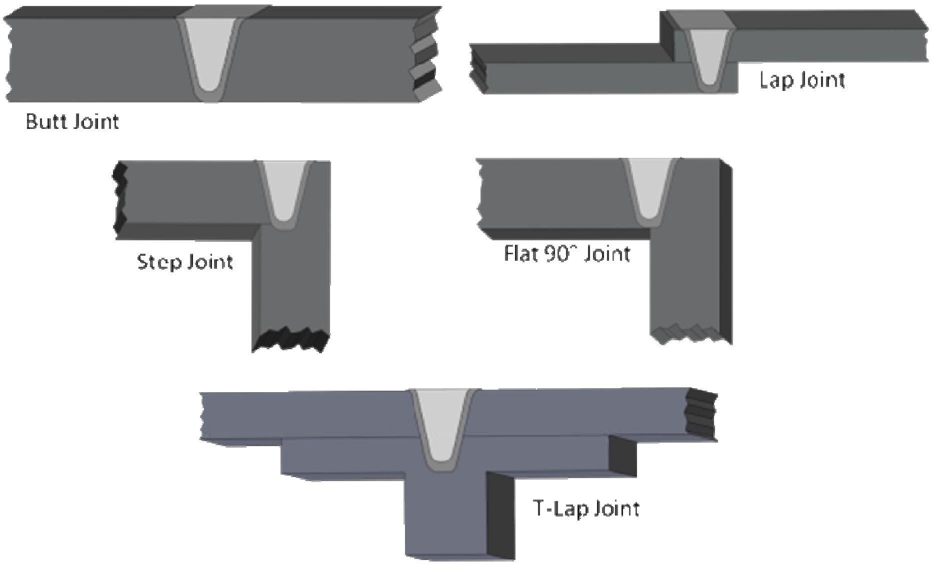
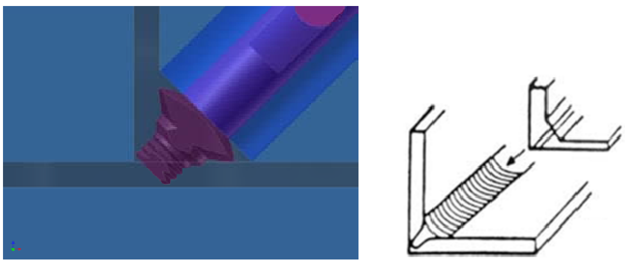


Fig. 2 – Joint configurations for FSW.

New research directions are oriented in tool development for the T joints (Fig. 3). At this moment at HZG are investigated different set-ups for geometry and welding parameters for this new tool.



(a) (b)

Fig. 3 – a) Welding tool for fillet connections; b) fillet joint.

The input parameters that govern the quality of the weld are the rotational speed (rot/min) ω, the travel speed (mm/min) U and the vertical force (kN) F_z. These input parameters have major influence to the process parameters: pin temperature, downwards forging force on the tool shoulder, tool torque, the forces from the weld in welding direction and perpendicular on the weld seam, parameters that define the mechanical properties of the welded element [7, 8].

In the early 2000 the process represented an important interest especially for the research. The results obtained during the years of research with good characteristics regarding the welding of aluminium alloys, with improved fatigue life and reduced residual stresses, the process known important application in the industry. Okubo et al. [9] observed that application of FSW on structural aluminium alloys improved the fatigue life in comparison with MIG, with comparable results on base material fatigue life characterisation and the distribution area of residual stresses was reduced, also the values of these were diminished. Kemal Kulekci et al. [10] found that fracture toughness of FSW lap joints increases exponentially as the hardness of the weld is reduced. Also new empirical equations were developed for fracture toughness and energy release rate based on the relation between the hardness and fracture toughness values.

In the following, this paper presents in the first instance the influence of the process parameters on the connections quality and second, personal results of the authors of the experimental application of the process on AA6082-T651 frequently used for many fatigue-critical parts of structures, mainly due to the fact of allying a relatively high strength, good corrosion resistance and high toughness to a good formability and weldability and AA5083-H111 known for exceptional performance in extreme environments and exceptional strength after welding [11, 12].

2. INFLUENCE OF THE PARAMETERS ON THE CONNECTION

During the FSW process a high temperature (below the melting point) is produced because of the stirring between the tool shoulder and the materials. The distribution of the temperature through the tool and the materials plays a very important role for the appearance of the residual strengths and for the distribution of the tensions in the welded elements [13, 14].

A recently study of Rodrigues et all [0] on two of the most used aluminium alloys for structural application presents the influence of pressure *P* versus weld pitch on the welding process. Here, weld pitch – other welding parameter, was defined as (1):

$$\frac{1}{\lambda} = \frac{\omega}{U} \left[\frac{\text{rot}}{\text{mm}}\right], \tag{1}$$

where ω is the rotational speed and U is the welding speed. The pressure P is defined as function of normal force F_z and tool parameters (D_s – shoulder diameter and D_p – pin diameter) (2):

$$P = \frac{F_z}{\frac{\pi}{4}\left(D_S^2 - D_p^2\right)}. \tag{2}$$

Frigaad et al. [16], has developed a numerical three-dimensional heat flow model for friction stir welding of age hardenable aluminum alloy based on the method of finite differences. The average heat input per unit area and time according to their model is (3):

$$q_0 = \frac{4}{3}\pi^2 \mu P \omega R^3, \tag{3}$$

where q_0 is the net power [W], μ the friction coefficient, P the pressure (Pa), ω the tool rotational speed (rot/s) and R is the tool radius [m]. The authors suggested that the tool rotation rate and shoulder radius are the main process variables in FSW, and the pressure P cannot exceed the actual flow stress of the material at the operating temperature if a sound weld without depressions is to be obtained.

The distribution of the residual stresses is in direct correlation with the temperature during the welding process and the heat input, frictional power. FSW is considered to be a steady-state process, which involve no energy storage and the mechanical power is converted into thermal energy. Based on these assumptions, the conservation of energy may be described as (5):

$$Q_g = Q_w + Q_a + Q_s + Q_v, \tag{5}$$

where Q_g is the weld power, Q_w is the conductive losses to the workpiece (welded elements), Q_a is the conduction losses to the anvil, Q_s is the conduction loss to the spindle, Q_v is the convective heat loss. The values of components of Eq. 5 are determined by (6)-(10):

$$Q_g = \omega\tau 2\pi R^3 \left[\frac{1}{3}\left(\frac{R_s}{R}\right)^3 + \frac{H}{R}\right], \tag{6}$$

$$Q_w = \frac{(T - T_0)2\pi k_w H}{\ln \frac{R_0}{R}}, \tag{7}$$

$$Q_a = 2\pi R_a k_a (T - T_0), \tag{8}$$

$$Q_s = \frac{k_{sp} \pi R_{sp}^2 (T - T_0)}{L_{sp}}, \tag{9}$$

$$Q_v = 2RHU\rho c(T - T_0), \tag{10}$$

where: ω is the spindle speed, τ is the flow stress of the material along the shear surface, R is the pin radius, R_s is the tool shoulder radius, H is the pin length, T is the shear surface temperature, T_0 is the ambient temperature, k_w is the thermal conductivity of the workpiece, R_0 is the initial radius of the conical pin, R_a is the bottom radius of the conical pin, k_a is the thermal conductivity of the anvil, k_{sp} is the spindle thermal conductivity, R_{sp} is the effective spindle radius, L_{sp} is the length of rod, ρc refers to the volumetric heat capacity of the workpiece material, U is the welding speed [17].

Based on these relations, the authors [18] proposed an improved variant of the heat index, considering only the parameters involved in the FSW process, such as geometry of the FSW tool, thermal properties of the workpiece and tooling. The new term is named AHI and can be used as (11).

This new defined parameter can be used to make an accurate scaling of the process parameters ω – rotational speed and U – the welding speed.

$$\mathrm{AHI} = \frac{(T - T_0)}{\tau} = A\frac{\omega}{B + U}, \tag{11}$$

where:

$$A = \frac{\pi R^2}{H\rho c}\left[\frac{1}{3}\left(\frac{R_s}{R}\right)^3 + \frac{H}{R}\right] \tag{12}$$

and

$$B = \frac{\pi R_{sp}^2}{\rho c}\left[\frac{k_w}{R_{sp}^2 R \ln\left(\frac{R_0}{R}\right)} + \frac{k_a}{HR_{sp}^2} + \frac{k_{sp}}{2L_{sp}RH}\right]. \tag{13}$$

During an extensive research work Wang et al. [18] concluded that higher welding speed also leads to a higher tensile residual stress. This apparently will negate the effect produced by the less softened microstructure. To quantify the influence of the residual stress, mechanical testing results on large welded pieces are needed. Once the influence of the residual stress is established, it should be possible to optimize the welding speed, or in general welding parameters for that matter, based on a compromise between the microstructure and residual stress to produce friction stir welds with desirable mechanical properties [19].

3. EXPERIMENTAL APPLICATION ON ALUMINIUM ALLOYS

In the last decades has increased the use of aluminium as a structural material for building and architecture for various reasons such as its light weight allows for easier rectification of structures for example façade panels, roofing, doors and windows in architecture, and ladders and platforms as building tools; its good inherent corrosion resistance and methods for protection such as anodising allow for durable outdoor exposure; the good strength-to-weight ratio that can be obtained.

For two aluminium alloys that are used also in the field of civil engineering, especially to bridge constructions, where one of the most important drawbacks is the corrosion, an experimental program was realized. The AA6082-T651 is very frequently used for many fatigue-critical parts of structures, mainly due to the fact of allying a relatively high strength, good corrosion resistance and high toughness to a good formability and weldability.

Aluminium AA5083-H111 is known for exceptional performance in extreme environments [20, 21].This alloy is highly resistant to attack by both seawater and industrial chemical environments.

For all welded samples bending tests were performed to investigate if there are surface or root defects. During the welding process temperatures were measured.

Fig. 5 and Fig. 6 present the measured temperatures in the vicinity of the welded connection, on top of the workpieces, and the weld pitch for the considered weldments.

From the temperature measurements it can be observed that a lower pitch value ($\lambda = U/\omega$) produced a higher temperature, meaning that a reduced welding speed (U) in comparison with the rotating speed (ω) introduces more heat, which involves an increase of the residual stresses. It also must be considered that a reduced welding speed offers more time for the material mixture, providing free of defects connections.

a) b)

Fig. 4 – Welding tool: a) flat shoulder with machined spiral flute, 15 mm diameter; b) threaded pin with thread M6L, conical tapered with three milled flats, 5 mm diameter.

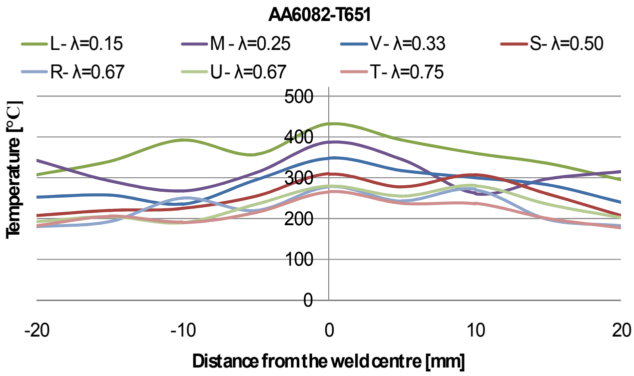


Fig. 5 – Temperature measurements on AA 6082-T651.

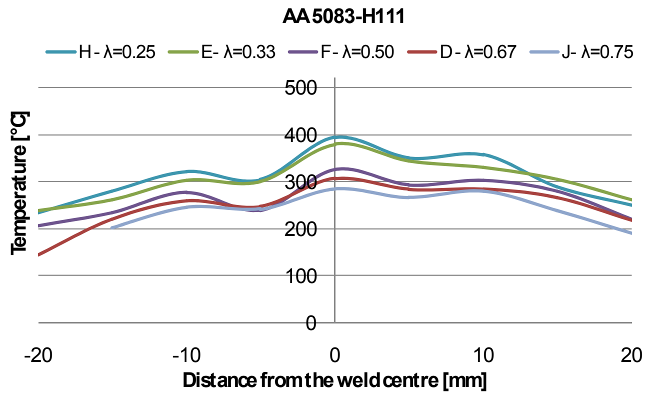


Fig. 6 – Temperature measurements on AA 5083-H111.

Based on these considerations together with the bending results, two sets of parameters (one for each alloy subjected to this experimental work) were used for the final connections. The selected parameters are presented in Table 1.

For the connections realized with these parameters detailed characterization (i.e. bending tests, hardness measurements, macrostructure analysis, tensile tests) were carried out in order to assess the performances of the analyzed alloys.

The macrostructure analyses presented free of defects connections, with grain size reduction in the weld seam (Fig. 7, Fig. 8). The weld nugget experiences high strain and is prone to recrystallization. During FSW, in comparison with usual welding process, there are three zones that can be observed: weld nugget, thermo-mechanical affected zone (TMAZ) and heat affected zone (HAZ) situated between TMAZ and base material (BM). TMAZ is situated in the close vicinity of the weld nugget and represents the transition from the nugget to HAZ. Unique to the FSW process is the creation of a transition zoneTMAZ between the parent material and the nugget zone. The TMAZ experiences both temperature and deformation during FSW. The TMAZ is characterized by a highly deformed structure. Furthermore, it was revealed that the grains in the TMAZ usually contain a high density of sub-boundaries [26].

Table 1

The parameters selection

6082-T651	Welding speed U [mm/min]	350
	Rotational speed ω [rot/min]	800
	Vertical force F_z [kN]	10
5083-H111	Welding speed U [mm/min]	400
	Rotational speed ω [rot/min]	800
	Vertical force F_z [kN]	10

The grain evolution between the base material and the welded affected material is evident. The recrystallization of the nugget zone during friction stir welding effectively wiped out any trace of the previous grain structure.

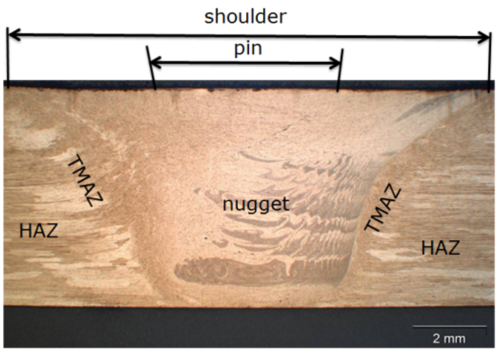


Fig. 7 – Macrostructure analysis on AA 6082-T651.

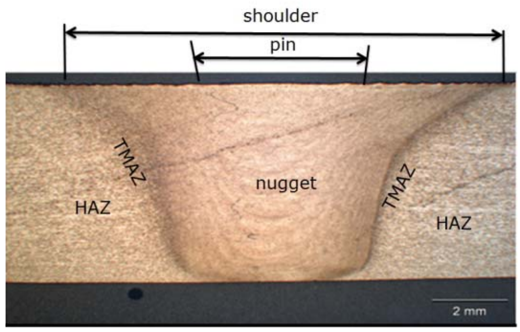


Fig. 8 – Macrostructure analysis on AA 5083-H111.

For AA6083-T651 the grain size was non-homogeneous, phenomena caused by the partial recrystallization [27]. By AA5083-H111 the changes are less visible; the grain size reduction is not significant as for the other alloy.

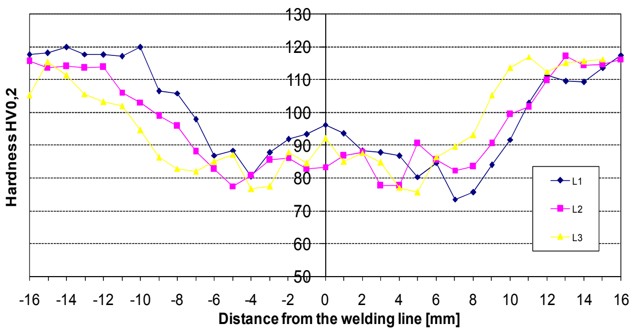


Fig. 9 – Hardness measurements on AA 6082-T651.

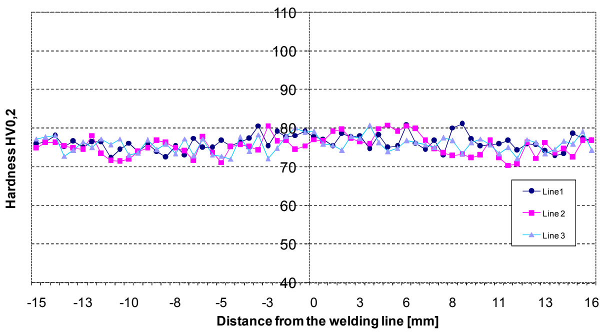


Fig. 10 – Hardness measurements on AA 5083-H111.

The hardness measurements were realized on three lines, disposed starting with 1 mm from the top surface of the section. Significant hardness drop can be observed especially to the welds of AA6082-T651 (Fig. 9). For AA5083-H111 the variations are not quite significant, only some small variations in the HAZ are visible (Fig. 10). These softening may caused the collapse in the HAZ of the tensile specimens (Fig. 11).

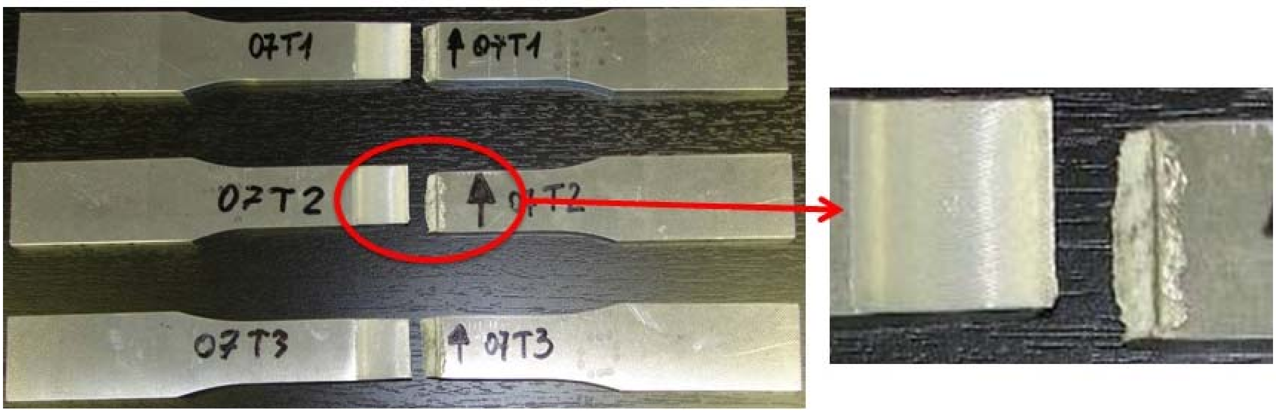


Fig. 11 – Tensile specimens breakage.

Also in this area is situated the end of the shoulder contact zone with the elements, and it may be considered as a defects concentration area.

Table 2

Tensile tests results and performance

	Base material **AA6082-T651**	Welded **AA6082-T651**	Performance	Base material **AA5083-H111**	Welded **AA5083-H111**	Performance
R_m [MPa]	316.2	247.83	78%	328.1	259.17	79%
$R_{p0.2}$ [MPa]	237.2	147.62	62%	166.9	127.23	76%

The results of the tensile tests (Table 2) of the welded AA6082-T651 can be correlated with the hardness measurements. The collapse of these specimens was in the hardness reduction zone (i.e. HAZ). For the AA5083-H111 the failure of the specimens was also in HAZ. This phenomenon was not observed during the tests on the calibrations weldments, where the same hardness reduction was found, but the collapse of the tensile specimens took place in the base material [28].

Further investigations for high cycle fatigue (HCF) and for low cycle fatigue (LCF) will be realized, in order to complete the characterization of the FSW for both studied alloys. Based on the presented results, it may be said that FSW is a proper connection for the AA6082-T651 and AA5083-H111, alloys used for structural elements.

4. CONCLUSIONS AND FUTURE DEVELOPMENT

FSW is considered to be the most significant development in metal joining in the last decades and is a ‘‘green’’ technology due to its energy efficiency, environment friendliness and considerably less energy consume. The joining does not involve any use of filler metal and therefore any aluminium alloy can be joined without concern for the compatibility of composition, which is an issue in fusion welding. For aluminium alloys the process can be considered known, considering the many industrial applications of the process. Still, because of the parameters variation and influence, detailed analysis for each aluminium alloy must be realized. It is important to evaluate the behaviour of the FSW connections under the HCF action in order to evaluate the possibility of using this type of welding to structures such as bridge decks and also to investigate the performances under LCF actions on such connections for structural components in buildings.

New research directions are oriented in the development of new welding tool configurations that allows realizing fillet joints – used on large scale to structural components.

The advantages of the process leads to new directions of applications to structural steels and also to high strength steels, which are more and more used in the field of civil engineering.

ACKNOWLEDGMENTS

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