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The influence of process parameters on mechanical properties and corrosion behaviour of friction stir welded aluminum joints

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Abstract

Aim of this study is to analyse how the process parameters affect the mechanical properties and the corrosion behaviour of butt joints obtained by friction stir welding (FSW). The experimental study was performed by the friction stir welding of sheets having a thickness equal to 4 mm and made of three aluminum alloys, namely AA7075, AA6060 and AA2024, considering all the combinations among the three materials and varying the process parameters, namely rotational speed and feed rate. Tensile tests were performed orthogonally to the welding direction on specimens having the welding nugget placed in the middle of gage length, while micro-Vickers tests were carried out on each specimen moving from the joint axis until the hardness of the base material was reached. The best conditions in terms of mechanical strength were obtained using the "intermediate" values of rotational speed, and, in general, when the process parameters result in low values feed rate per unit revolution (F/S), that corresponds to the higher thermal contribution to the joint region. Since in many industrial applications the mechanical resistance is not sufficient for completely describing the joint reliability, further local corrosion potential measurements and four-point bending tests were performed to evaluate the corrosion behaviour and stress corrosion cracking susceptibility of FSW Joints. The tests were carried out on prismatic specimens obtained by FSW joints of the same alloy (7075-7075 and 2024-2024) and mixed joints (7075-2024). No specimens failed during the test. It was observed that the lower the hardness, the more anodic the corrosion potential. In these zones an intense localized attack takes place in the HAZ due to the presence of precipitates. No systematic correlations between the parameters and the resistance to corrosion were observed. The presence of preferential corrosion sites was confirmed also by means of long time immersion tests.

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1. Introduction

Friction Stir Welding (FSW) technology, patented by TWI in 1991 [1,2], represents a valid solution for joining difficult to be welded materials (such as Al, Ti and Mg alloys but also Advanced High-Strength Steel [3]).

One of the most significant aspects of this technology is the achievement of the joining by maintaining the solid state of the material. The rotation of the tool and the movement along the joint axis cause an increase in material temperature (for the effect of friction between tool and workpiece and within the stirred material) and the plasticization of the material (for the combination of the mixing effect of the tool pin and the pressure applied by the tool shoulder) that cause the formation of a solid bonded region [4]. This technology permits the welding in several configurations and also the joining of dissimilar alloys [5-7] and it is used in several industrial applications such as automotive, aerospace and naval sectors [8,9].

The FSW technology has a large interest especially for high resistance aluminum alloys (e.g. 2000 and 7000 aluminum alloys series, because of their aeronautical use), which are difficult to be joined with traditional techniques which alter the microstructure obtained during age hardening. The high plastic flow and the heat generated by FSW may result in remarkable microstructural modifications and local changes of material characteristics [10,11].

For these reasons, it is very important to understand the effects of process parameters and process setup on the weld quality. Several Authors studied these aspects with particular attention to the quality of FSW joints in terms of mechanical properties (UTS, fatigue resistance etc.) [12-14]. For example, in [15] the Authors evidenced how some very important issues related to the mechanical properties of aluminum friction stir welded joints are process parameters such as feed rate, rotational speed, tool geometry and pin axis inclination. Tool rotational speed has been considered as one of the most important process variable: high rotational speeds may raise the strain rate, so affecting the re-crystallization process [16]. Moreover, some authors showed how high welding speeds are related to low heat inputs, which gives rise to faster cooling rates of the joint [17]. This can reduce the extent of metallurgical transformations taking place during welding (such as solubilisation, re-precipitation and coarsening of precipitates) and hence the local strength of individual regions across the weld zone. Based on these considerations, the ratio between the tool feed rate and the rotating speed can be considered as a relevant parameter in determining the mechanical strength of the joints. Other Authors observed that, welding by FSW A356 and 6061 aluminum alloys, the joint fabricated using low tool traversing and rotational speed, exhibits substantial improvement in bond strength [18]. In [19] empirical relationships have been developed to predict the tensile strengths of friction stir welded AA1100, AA2219-T87, AA2024-T3, AA6061-T6, AA7039-T4 and AA7075-T6 aluminum alloy joints. Other authors found that there is an optimal rotational speed range of the pin and that too low and too high speeds correspond to a low quality of the joints [20], demonstrating that these parameters can be optimized for obtaining sound parts.

In addition, particular attention has to be paid due to the well-known susceptibility of the copper-aluminum and zinc-aluminum alloys to stress corrosion cracking [21]. Despite the enhanced properties, the added elements introduce higher degree of heterogeneity due to the presence of secondary phases or termed constituent particles [22]. Corrosion behaviour can be mainly affected by the presence – size and distribution – of such phases, modifying the anodic and cathodic behaviour of the zones of joining. [23,24]. Several works describing corrosion morphologies that can occur also concomitantly in form of localized corrosion, e.g., galvanic corrosion, pitting, dealloying or intergranular attack [25-27] were found, but very few data regarding the combination of different alloys and the systematic correlation between mechanical properties and corrosion behaviour can be noticed. Under such considerations, the corrosion behaviour can be significantly influenced by welding parameters and a strict correlation between them and alloy macro and microstructure has to be further investigated [28].

As a general remark, it is possible to assert that the FSW process parameters have significant effects on the joint properties, sometimes different for dissimilar alloys, and their influence on the joint characteristics and behaviour is not yet fully understood.

Aim of this study is to analyse how the process parameters affect both the mechanical properties and the corrosion behaviour of butt joints obtained on different aluminum alloys by FSW. The experimental study was performed by the friction stir welding of sheets made of three different aluminum alloys, namely AA7075, AA6060 and AA2024; all the combination among the three materials were also taken into account.

2. Experimental procedure

2.1. FWS experimental set up

The FSW butt joints were carried out on sheets having a thickness equal to 4 mm by means of a CNC machine tool. Three different aluminum alloys, namely AA 6060T6, AA2024-T3 and 7075-T6, were used for this purpose and the combination among the three materials was also taken into account (6060-2024, 6060-7075, 2024-7075). Table 1 shows the mechanical properties of the materials. Sheets of 200 x 80 mm were welded by using tools with smooth plane shoulder (16 mm diameter) and pin having a frustum of cone shape (pin maximum and minimum diameters equal to 6 and 4 mm, pin height equal to 3.8 mm). The tests were carried out varying tool rotational speed on three levels (S=1000, 1500, 2000 rpm) and feed rate on three levels (F=10, 35, 60 mm/min). Three welding repetitions were carried out for each combination of parameters for evaluating the process repeatability.

Table 1. Mechanical properties of the aluminum alloys.

Mechanical properties	AA6060T6	AA2024T3	AA7075T6
Yield strength [MPa]	214	345	511
UTS [MPa]	241	459	578
Max strain [%]	15	17	11

2.2. Mechanical testing of the joints

The mechanical properties of the joints were evaluated by means of tensile tests executed orthogonally to the welding direction, according to UNI EN ISO 6892-1:2016. The specimens with 160 x 20 mm, having the welding nugget placed in the middle of gage length were tested using a testing machine Galdabini with a load cell of 50 kN. The tests were carried out under speed control (7.6 mm/min) and a pre-load equal to 0.5 kN. The joint tensile resistance was evaluated as a function of the different process parameters and 3 specimens for each welding condition were tested. The influence of process parameters on both the material structure and the joint strain hardening was evaluated by measuring the microhardness distribution in the welded sections for all the tested conditions.

Micro-Vickers tests were carried out using a load of 2 N and a permanence time equal to 15 seconds. A grid composed by three lines of indentations (moving from a distance of 1 mm to a distance of 3 mm from the upper surface) was executed on each specimen. On each line the distance among the indentations was equal to 3 mm. The tests were executed moving from the joint axis to the base material until the hardness of the base material was reached.

2.3. Corrosion tests

Local corrosion potential measurements and four-point bending tests have been performed to evaluate the corrosion behaviour and stress corrosion cracking susceptibility of FSW Joints. The tests were performed on 4x20x160 mm prismatic specimens obtained by FSW joints of the same alloy (7075-7075 and 2024-2024) and mixed joints (7075-2024). Several processing parameters were studied: feed rates of 10-35 mm/min and tool speed of 1000-1500 rpm. The specimens were polished by emery papers up to 1000 grit and degreased in acetone in ultrasonic bath for 5 minutes. After polishing, the specimens were stored in still air for 48 hours to allow the formation of the natural protective film. Free corrosion potential measurements have been carried out by moving a 1 mm capillary equipped with a Standard Calomel Electrode (SCE) over the specimen length every 10 mm. The specimens were pre-soaked for 48 hours in distilled water to achieve stable potential values. The potential profile was obtained in the central zone of the specimen to avoid border effects. The specimens were covered by a thin layer of distilled water to permit the execution of the potential measurements. Four-point bending tests have been performed according to ASTM G39. The specimen is put inside the bending device to attain uniform tensile strain distribution over the welded surface. The specimens were loaded up to the 80% of the tensile strength of FSW joints derived by tensile tests. Four glass cylinders were used to avoid galvanic coupling between the stainless steel specimen holder and aluminum. The specimens were exposed in a cell filled with about 30L water with 35 g/L sodium chloride for more than 40 days. At the end of the exposure tests, the specimens were unloaded, washed in distilled water and rinsed with acetone in ultrasonic bath. The surfaces were then observed by means of optical microscope up to 600 magnifications and scanning electron microscope equipped -with energy dispersive x-ray analysis.

3. Analysis of the results

3.1. Mechanical properties

Figure 1 shows the mechanical property behaviours for the joints in terms of UTS. The tensile strength is reported as a function of the feed rate per unit revolution (feed/speed) [mm/rev]. This parameter is also an index of the thermal power transferred to the joint region during the process. Among all the 9 process parameter combinations, only those corresponding to the extreme values of the process conditions range and the central point are reported in the graph. Each marker represents the average of three repetitions. The joints obtained using AA7075, AA2024 and their combination show a similar behaviour: in particular, the best conditions in terms of UTS are achieved for low-medium values of feed rate per unit revolution (F/S = 10/1000 mm/rev, F/S = 35/1500 mm/rev), that correspond to high thermal contributions to the joint region. The effect was only noticed for age hardenable alloys and this could be related to overaging due to the permanence at high temperature. This is not visible for the joints considering AA6060 since this alloy has a lower UTS limiting the positive effects of the lowest F/S values.

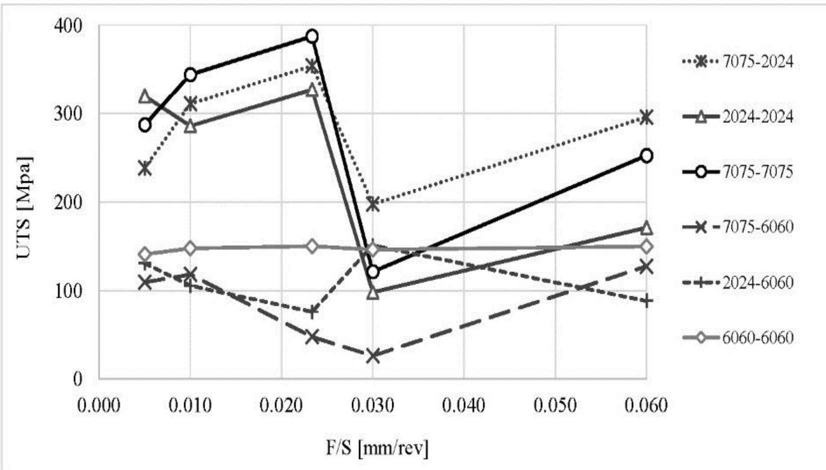

Fig. 1 The tensile strength of the joints (UTS) as a function of the feed rate per unit revolution (feed/speed) [mm/rev].

The measurements of free corrosion potentials along the FSWed joint is reported – as a title of example – for 2024, 7075 and mixed joint at the F/S ratio that maximize the tensile strength of joints, equal to 0.023. FSWed 7075 alloy shows two well defined softened zones in the thermo-mechanically affected zone, whilst the minimum of hardness was obtained in the centre of the nugget of alloy 2024. Good correlation between microhardness profiles and local free corrosion potential measurements can be noticed. The mixed joint - far from the nugget - shows the same behaviours of the two different base alloys welded at same parameters. Free corrosion potential of mixed joint is low in the zone of 7075 base metal and it increases moving across the nugget to values typical of the base metal of alloy 2024. Such behaviour is due to metal partial mixing in the joint and precipitates distribution.

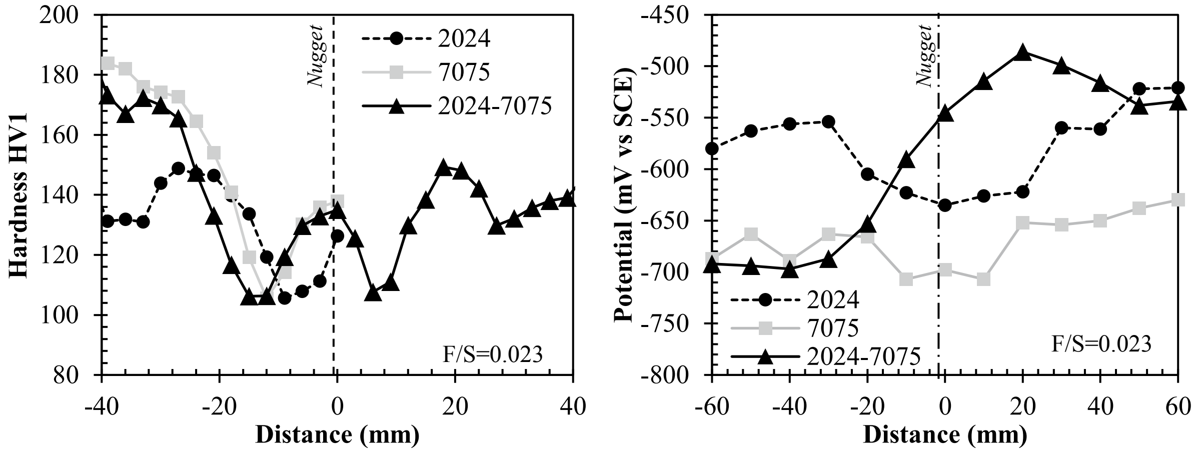

Fig. 2 Hardness (left) and free corrosion potential values (right) along the FSW joint for alloy 2024, 7075 and mixed

3.2. Corrosion morphology

At the end of long exposures tests, the loaded specimens did not show cracks due to SCC. Alloy 7075 shows a severe attack in the thermo-mechanical affected zone (Fig 4a) and it propagates becoming exfoliating at the rolling bands of the sheet. Microstructure significantly affects the attack morphology. The attack is limited in the nugget for 2024 alloy (Fig. 4b) and the presence of large localized attack can also be evidenced, which propagates with a morphology (Fig. 4d) strictly related to the presence of copper rich (Fig. 4e-f) sub-micrometric precipitates. In the mixed joint, corrosion is more severe and it is limited in the thermo-mechanically affected areas of 7075 alloy, whilst only localized attack in correspondence of larger precipitates of alloy 2024 can be observed. $MgZn_2$ precipitates of alloy 7075 are anodic respect to the aluminum matrix, as reported by Andreatta et al. [24], they are very reactive and they are prone to grow preferentially at the grain boundaries. Aluminum matrix is active in such areas, as demonstrated by low corrosion potentials. The presence of sub micrometric copper-rich precipitates can be noticed in the zones of nugget where grain recrystallization occurs, leading to a free corrosion potential decrease due to the less noble potential of the aluminum matrix. Copper rich precipitates are nobler compared to aluminum [29] and they behave as cathodes. At the interface with the precipitates of copper, alkalinisation produced by reduction of oxygen dissolves the passivity film of the aluminum matrix, promoting active dissolution. As stated by K.D. Ralston et al. [29] due to the high electrical resistivity of the passive film of alumina, the effect of the copper-rich precipitates is limited to the adjacent matrix and does not extend to remote areas.

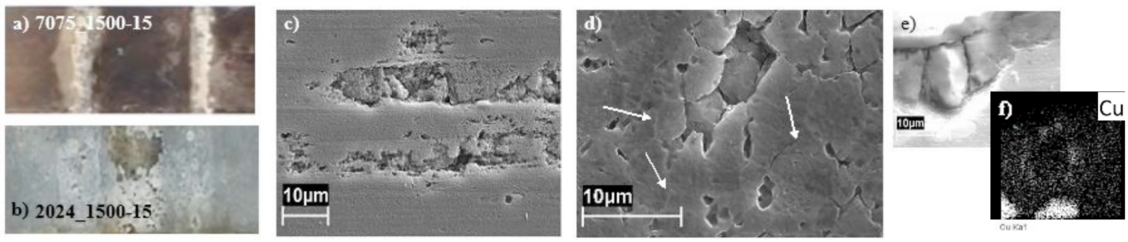

Fig. 3 Corrosion morphology of the 4PBB specimens after 1000 hour of immersion

4. Conclusions

The paper analyses the effect of the process parameters on the mechanical properties and the corrosion behaviour of butt joints obtained by friction stir welding (FSW). The best conditions in terms of mechanical strength were obtained using the "intermediate" values of rotational speed, and, in general, when the process parameters result in low values feed rate per unit revolution (F/S), that corresponds to the higher thermal contribution to the joint region. Free corrosion potential measurements and four-point bending tests were performed to evaluate the corrosion behaviour and stress corrosion cracking susceptibility of FSW Joints. No SCC occurrence was evidenced. A good correlation between microhardness and free corrosion potentials was noticed. The lower the hardness, the more anodic the corrosion potential. Severe localized attack occurs in the heat affected zones owing to the presence of sub micrometric precipitates. No systematic relationship between the process parameters and the corrosion behaviour can be observed. The presence of preferential corrosion sites was confirmed also by means of long time immersion tests.

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