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Fatigue Resistance of AA2024-T4 Friction Stir welding Joints: Influence of Process Parameters

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Abstract: In the last years friction stir welding (FSW) has reached a quite large diffusion in the welding of aluminium alloys, difficult to be welded with traditional technologies. The objective of this investigation was to investigate the influence of FSW process parameters on the fatigue strength of the developed joints. Moreover, in order to improvement the strength of joint, the effect of a post-welding treatment has been highlighted; what is more a surface finish treatment has been developed with the aim to eliminate the stress concentration caused by welding process on the surface of the joints. Finally, the fracture locations have been determined in order to fully understand and improve mechanical the process mechanics and the final local material properties of joints.

keyword: Fatigue, Process parameters, Post-welding and surface treatment.

1 Introduction

Friction stir welding (FSW) is utilized to weld aluminium and titanium alloys; actually such material are difficult to be welded with traditional technologies. Through FSW process is possible to joint thin sheets without defects, preparations of joints and filler material, in this way the operating costs are low. In fact, the process is a solid-state welding: no melting of the base material is observed and in this way the cracks and porosity often associated with fusion weldings are eliminated. At this time, FSW finds wide use in aeronautics and naval applications but actually the studies are still going on. The process is developed utilizing a rotating tool which is inserted between the edges of the sheets to be welded and moved all along the welding line; the heat flux is generated both by the frictional forces work and by the plastic deformation work decaying into heat. The tool is generally represented by a pin end and a shoulder which improves the amount of heat supplied. The supplied heat makes determines the softening of the blanks material without reaching the melting temperature [Shigematsu, Kwon, Suzuki, Imai and Saito (2003), Guerra, Schmidt, McClure, Murr, and Nunes (2003), Czechowski (2005), Lomolino, Tovo, and dos Santos (2005), Zhou, Yang, Luan (2005)]. In Fig.1 a sketch of the welding process is shown:

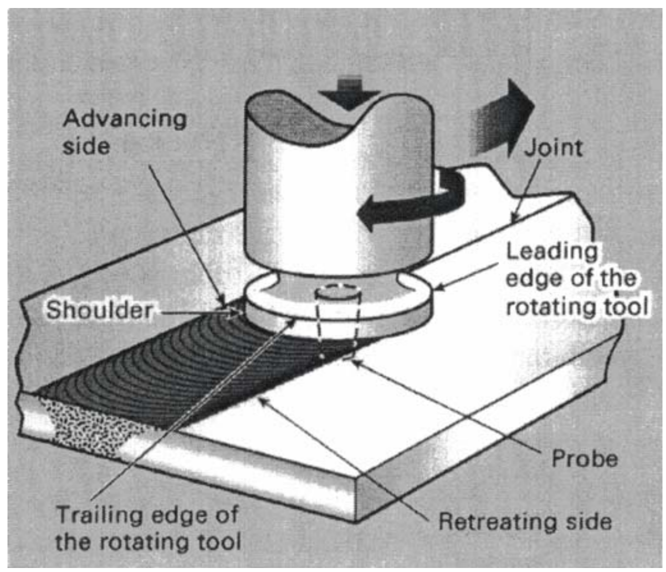

Figure 1 : Schematic representation of the FSW process.

2 Experimental

2.1 *Material*

The base material utilized in this investigation was AA2024-T4 aluminium alloy. The high mechanics performance and the low specific weight are demands characteristics in aeronautics and naval applications. The T4 condition confers high mechanical properties which are comparable with some steels. The AA2024-T4 alloy contains the manganese to increase thoughness and ductility. The blanks were produced as extruded flat profiles in the form of 3 mm plates. During the welding process the rolling direction was not considered, that can cause

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Table 1 : AA2024-T4 mechanical properties.

AA2024-T4	
σ_r[MPa]	470
σ_y[MPa]	324
$\sigma_{l,rf}$[MPa]	175
E [GPa]	73.1
ν	0.33

a variation in fatigue strength. Otherwise, recently investigations have not showed significant changes in the fatigue performances with the rolling direction. The experimental analysis on the AA2024-T4 aluminium alloy has been furnished the following (Tab.1) static and dynamic mechanical properties.

2.2 FSW process and parameters

FS welds were produced through a traditional milling machine. Each test was developed as follows: two 100x100x3 plate were blocked and placed side by side in order to realize the weld. The tool was characterized by two coaxial cylinders with different diameter which are called pin and shoulder. The tool depth was checked through a micrometer. The utilized pin was cylindrical with a 3mm diameter and an height of 2.8mm. In Fig.2 is showed the tool geometry.

The most relevant FSW process parameters influencing the welding process are:

Rotation speed of tool R [rpm].

Welding speed of tool V_f [mm/min.].

Tool sinking into the blanks ΔH.

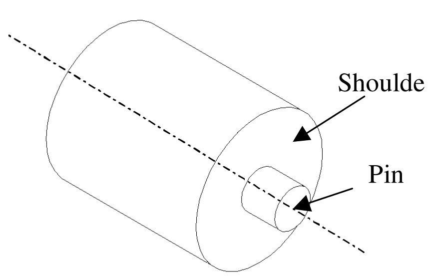

Figure 2 : Representation of tool geometry used in the experiments.

Other parameters influence the welding process as shape and the geometry of the pin. For example a thread pin can determine a better stir effect on the material while a low height of pin cause the presence of defect along the welding line. These parameters were not taken into account during the present study.

Former investigations [Buffa, Cirello, Fratini and Pasta (2004)] have shown that the mechanical properties of the joints are influenced by heat supplied for unit of length during the welding. Generally, the static and dynamic performance of FSW joint improves for large amount of the supplied heat [Liu, Fuiji, Maeda and Nogi (2003), Barcellona, Buffa and Fratini, (2004)]. It can be asserted that the supplied heat is the most relevant parameter which determines the mechanical properties of the joints and it can be roughly expressed as the ratio between the welding speed (tool feed rate) and the tool rotation speed. This ratio is called revolutionary pitch [mm/rev.]. An optimal value of revolutionary pitch can be determined in order to maximize the mechanical characteristics of the FSW joints. This value depends on material properties of the considered alloy. Generally, in traditional welding processes, defects and voids rise during the solidification phase of the weld which happens with large gradients of temperature. In FSW, in turn, defects are introduced along the welding line and beyond the probe (roots); these voids influence considerable the fatigue strength of FSW joint [Dickerson and Prydatek (2003)] causing the fracture in few cycles. In FSW the presence of defects is due to insufficient stir action, due to an ineffective geometry of the probe and more often to an insufficient heat flux.

2.3 Microstructural analysis of a FSW joint

A microstructural analysis of a transverse section of a FSW joint shows three main zones, each of which is characterized by different dimensions and shape of grains [Liu, Murr, Niou, McClure and Vega (1997)]. These zone are showed in Fig.3:

Heat affected zone (HAZ).

Thermomechanically-affected zone (TMAZ).

Nugget.

First HAZ zone is characterized by a swell crystalline grain. That is due to high temperature reached in its zone. It shopuld be observed that the probe do not interests directly the HAZ region. Then the TMAZ follows

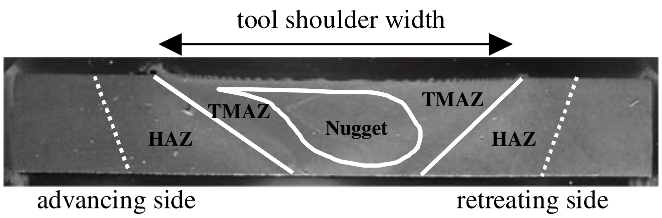

Figure 3 : Microstructural analysis of a FSW joint.

approaching the welding line. In the TMAZ zone, the mechanical effect adds to the thermal one and the material structure is highly distorted and the grain nearby the nugget begins to crush itself. Finally, the grain in the nugget shows recrystallization phenomena, the grain dimension is much finer than base material one.

2.4 Experimental plan

In order to highlight as FSW joint is influenced by main parameters, we have varied the rotation and welding speed and tool depth. So the heat supplied during the welding is considered through the mentioned parameters which also regulate the revolutionary pitch. On the basis of former investigations the revolutionary pitch has been varied between 0,1 and 0,3 mm/rev. which correspond respectively to high and low levels of supplied heat. No value lower than 0,1 mm/rev. has been investigated because it causes high detriment of joint. Three different tool depths have been considered. Therefore the experimental plan has been established in according with factorial logic depicted in Tab.2:

Table 2 : Experimental plane of welding and ID.

ΔH [mm]	R [rpm]	V_f [mm/min]	ID
2,85	715	143	A
2,85	715	71	B
2,85	715	100	C
2,85	715	215	D
2,8	715	143	E
2,9	715	143	F
2,85	490	143	G
2,85	1040	143	H

2.5 Tests

The fatigue tests were carried out through an Instron 1603 resonance machine with a 100kN load cell which allows to achieve high loading frequencies. First, the fatigue curve and endurance fatigue limit were determined for base material. The stress ratio was chosen equal to 0,17 in order to diminish the effect of load itself on the specimen and to ensure a value of preload. The number of cycles to fracture was found for 10^6 cycles although in literature was considered the for 10^7 cycles. That can be considered permissible since a change in the slope of the fatigue curve for 10^6 cycles was already obtained. The loading frequency was about 105Hz.

3 Results and discussion

3.1 Tensile strength test results

The tensile strength was determined for each set of joints (see Tab. 2). The values have been compared to tensile strength of the parent material. The comparison has shown a resistance of the joint up to 92% of the base material one. In Tab.3 the average values of tensile strength for each set of joints is reported.

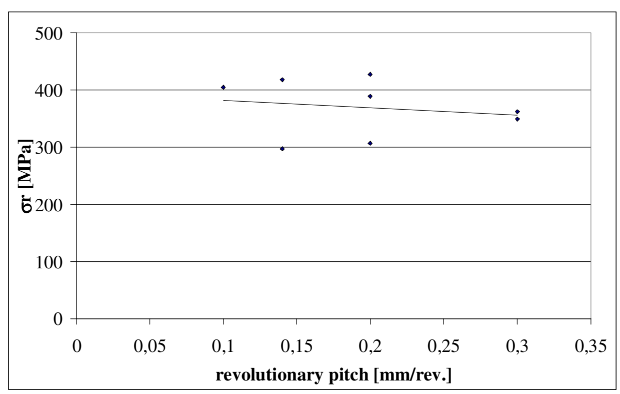

Figure 4 : Tensile strength as function of revolutionary pitch for each kids of joint.

A more careful analysis can be carried out representing the tensile strength as function of the revolutionary pitch (Fig.4).

It should be observed that tensile strength diminishes at the increasing of the revolutionary pitch, i.e. for lower heat supplied. Such a result has been found in former investigations carried out on AA6082-T6 aluminium alloy. Fracture analysis of joint have shown different fracture modalities. Fractures along the welding line has

Table 3 : Ultimate tensile stress for each set of joints.

Rev. Pitch [mm/rev.]	ΔH[mm]	R[rpm]	V_f[mm/min]	ID	σ_r[MPa]
0,2	2.85	715	143	A	307.8
0,1	2.85	715	71	B	404.4
0,14	2.85	715	100	C	417.8
0,3	2.85	715	215	D	349.1
0,2	2.80	715	143	E	389.1
0,2	2.90	715	143	F	427.4
0,29	2.85	490	143	G	362.2
0,14	2.85	1040	143	H	297.2

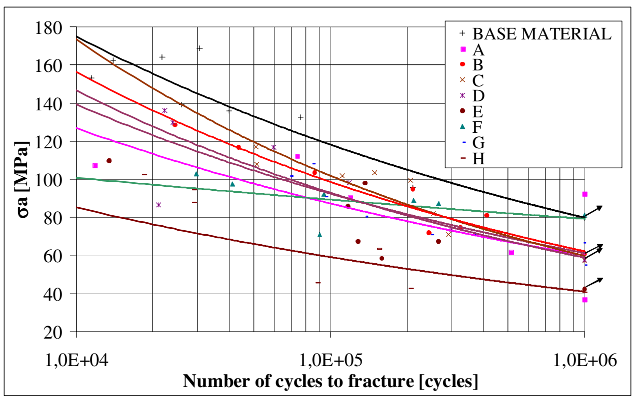

Figure 5 : Fatigue curve of base material and FSW joints.

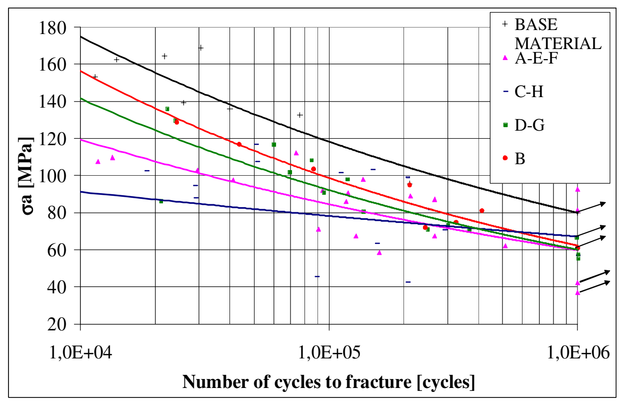

Figure 6 : Fatigue curve as function of revolutionary pitch.

been found for specimens with roots defects (series H). Besides for increasing values of revolutionary pitch, the fractures show an evident necking.

3.2 *Fatigue test results*

The applied loads for tests has been selected on the basis of the knowledge acquired with tensile strengths. Subsequently mean and alternative load are determined for a stress ratio R=0.17. The alternative load σ_a as function of the number of cycles to fracture has been shown in a semi-logaritmic plane. In Fig.5 the fatigue curves and experimental fracture data for each sets of joint is shown.

It should be observed that the fatigue curves are quite close each other, except H and E series for which the presence of defects (H series) and insufficient stir (E series) has determined a lower resistance. So we could assert that variations of process parameters do not degrades the fatigue performance of FSW joint. The reached result shows an 80% efficiency of the joints with respect to the base material. This results are considerable in comparison with other welding methods as MIG and TIG [Ericsson and Sandstrom (2003)]. In order to better analyse the obtained results, the experimental values were grouped as function of the revolutionary pitch, i.e. the supplied heat.

We can observe from Fig.6 that the best curve is the one obtained for the B series with 0.1 mm/rev. of revolutionary pitch which have a large value of the supplied heat flux during the welding process. Moreover for lower levels of the heat flux, the endurance fatigue limit degrades. Such considerations are in accord to former studies carry out on AA6082-T6 aluminium alloy [Buffa, Cirello, Fratini and Pasta (2004)].

3.3 *Fracture analysis of fatigue tests*

The growth and propagation of fatigue cracks have been found for each set of the developed joints. The high per-

Figure 7 : Fracture in the HAZ zone and depicting of changing of crack path.

Figure 9 : Fracture at the interface between the nugget and TMAZ zone.

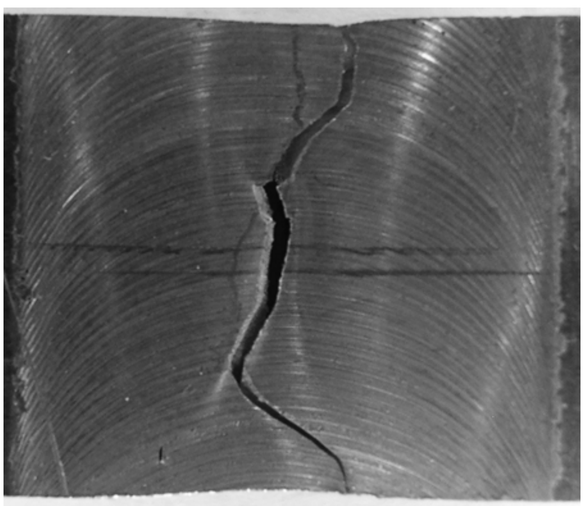

Figure 8 : Fracture along the welding line. It shows an evident strizione.

formance of the joints has determined the occurrence of some of the fractures in the base material of the joints. Usually fractures occur in the advancing side of the joints and rarely in the retreating one. The fracture in the HAZ zone, Fig.7, depends also on the rough surface. In fact, the position of crack initiations occurs always in the top surface of the joints where the prints of the tool shoulder edge are found. This zone presents a stress concentration caused by pressure due to shoulder during the welding process. This two effects create a crack on the edge of the joint in perpendicular direction respect to load. Then the crack propagates through the section determining the fracture of the joint. The crack changes the direction towards the applied loading direction. The changing of crack path is more evident for some value of process parameters [Sutton, Reynolds, Yang and Taylor (2003)] and depends from mechanical properties of material.

The fracture along the welding line, Fig.8, can be attributed to the voids propagation known as "tunnel defects". In this case the defect raises in correspondence of the welding roots and it propagates towards both edge of the joint. The fracture quickly develops since it is influenced by tensile residual stresses at the bottom of the joint which open the crack tip.

As was already observed, the heat supplied to the joint has caused an increasing of the dimension of grain in the HAZ and TMAZ zones. In this way in such zones the material shows a softening effect with respect to the nugget area. Otherwise the nugget increases its toughness with increasing of rotation speed of tool. The fine dimension of grain is fundamentally due to the mechanical stirring effect of the pin. In fact, the rotation speed and the tool feed rated give rise to a demolition action which reduces the grain size. In turn in the TMAZ the tool action determines the structural distortion of the grains. In this way the different microstructures at the interface between the nugget and TMAZ can cause fractures. In Fig.9 is showed an example of the mentioned fracture.

Besides, it should be observed that the 30% of fracture for all series investigated happened in the base material of the joint. Such a result can be thought as an interesting consequence because demonstrates an efficiency of joint comparable with the base material. That is also asserted by the high level of efficiency reached by joint in the fatigue curves.

4 Effect of post-welding and surface treatments

In order to improve the mechanical properties of resistance of joint, we have thought to analyze the hardening effect through a T4 post-welding treatment and to eliminate the stress concentration consequential to the welding process through a milling process. So we have considered the series B for these investigations because it has exhibited the best fatigue strength.

4.1 Post-welding effect

The scope of the post-welding treatments was to reproduce the mechanical characteristic of the material before the welding. In fact the T4 treatment is a hardening process which confers to AA2024-T4 alloy improved mechanical performances. Besides, we can suppose that the treatment improves the toughness in the HAZ zone which is a zone of FSW joint where softening occurs. Generally the T4 post-welding treatment increases the endurance fatigue limit and the tensile strength.

New fatigue and tensile tests on the treated specimens were carried out. The tensile strength of the treated joints (series TT) was very lower than no-treatment joints (series B). In the Fig.10 the fatigue curve of the treated joint is shown and compared with both fatigue curve of set B and base material series one.

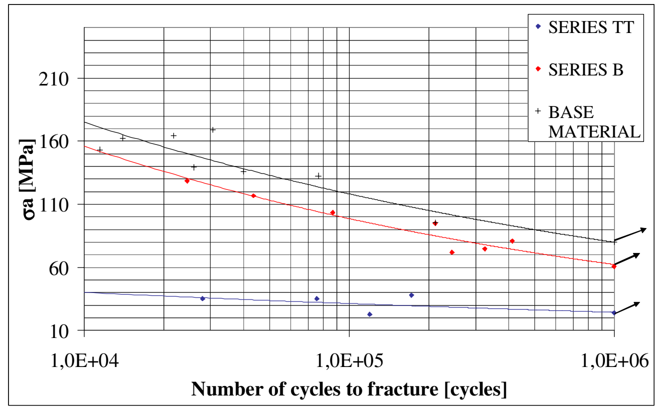

Figure 10 : Fatigue curve of treated specimens in comparison with B and base material curves.

It should be observed that both the fatigue curve and the endurance fatigue limit are lower than the values obtained for B series. Such a results can be attributed to the changing of the microstructure of the grain which is showed in Fig.11.

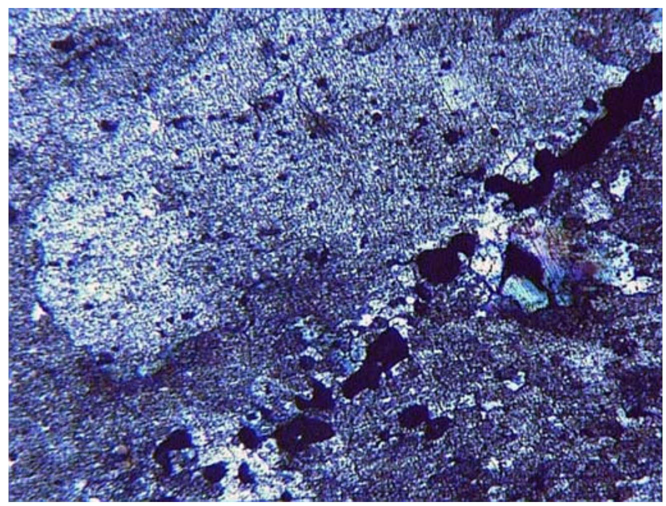

Figure 11 : Microstructural of the grain at the interface between the nugget and TMAZ zone (125x).

In particular the microstructure of the grain resulted worse presenting voids. The cause of the bad structure of the joint is the difficulty to develop the T4 treatment and what is more the combination of the residual stresses introduced by T4 treatment with the residual stress due to welding process. The combination of residual stress stretch to crack the joint into the zone at the interface between the nugget and TMAZ.

4.2 Effect of surface treatment

Analyzing the initiates of crack propagation for each joints, it was highlighted that they were found mainly on the top surface of the welding rather than in correspondence of the root. In particular the cracks start nearby the texturing caused by shoulder. In this way, a surface finishing operation, i.e. a milling process, was developed in order to definitively improve the surface finish of the joints, avoiding crack initiation. Furthermore, a new fatigue curve (series S) was created. In Fig.12 the fatigue curve of specimens with surface finish is reported and it is compared with the B and base material fatigue curves.

The endurance fatigue limit is lightly lower than endurance fatigue limit of the B series. Such a result can be considered unexpected. In fact the milling process has modified the initiate of crack propagation which is moved in all case from the top surface on the root side of the welding. This consequence reveals that the factors influencing the crack growth are the stress concentration and rough surface. In fact, now for the milled specimens the crack starts close to the root of the welds.

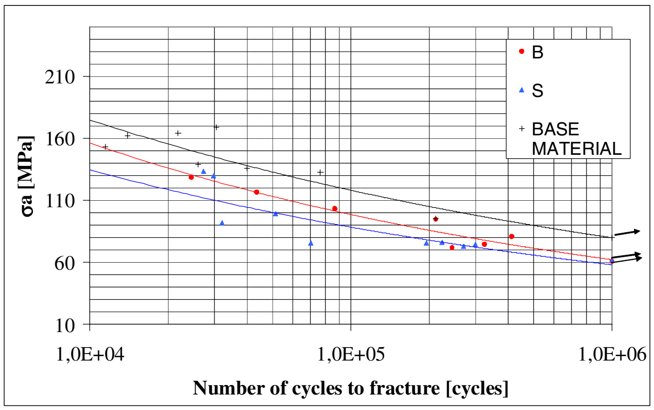

Figure 12 : Fatigue curve of milling specimens in comparison with B and base material fatigue curves.

Generally the crack growth rate depends by the effect of the applied load and of residual stresses. Many studies [Bassu and Irving (2003), John, Jata and Sadanada (2003), Peel, Steuwer, Preuss and Withers (2003)] have shown that such residual stress in correspondence of HAZ zone are compressive stresses at least at the top layers of the joints. Then, the milling process had also removed the beneficial compressive residual stress. So the crack growth rate has been improved with respect to the not finished specimens. Summing up the milled specimens have a bigger crack growth rate caused by the absence of the compressive residual stress therefore a lower fatigue curve is obtained.

5 Conclusions

The fatigue strength of FSW joint is slightly influenced by process parameters of the welding. In this way it can be assumed that FSW is a valid technique to weld with good efficiency the material as aluminium alloy which are difficult to be welded with traditional techniques. The efficiency of FSW joints reached even 92% in tensile strength with respect to base material while 82% was obtained for fatigue tests, better than MIG and TIG techniques [Ericsson and Sandstrom (2003)]. The main parameter of FSW process is the revolutionary pitch which controls the supplied heat flux. An optimum value of revolutionary pitch was found out for which the best mechanical properties were obtained. For AA2024-T4 the obtained value was 0.1 mm/rev. but generally it depends on material properties.

The post-welding and surface treatments did not allow to improve the already good efficiency of FSW joints.

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