Behaviour Simulation of Aluminium Alloy 6082-T6 during Friction Stir Welding and Tungsten Inert Gas Welding

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Abstract: - The investigation focussed on the modelling by finite elements of heat transfer and Von Mises stress field and simulation of the tensile test when applying friction stir welding (FSW) and classical Tungsten Inert Gas (TIG) welding at the aluminium alloy AA 6082-T6 butt joints performing. Both the numerical and experimental results revealed big differences between the behaviour of the base materials welded by FSW and TIG. It is important to study the heat transfer mode during the welding process, because it has a huge influence on the mechanical properties changes of the welded joint. The capability of a welded joint to resist breaking under tensile stress is one of the most important and widely fundamental mechanical tests used in the analysis of the materials behaviour at welding. Tensile properties indicate how the material will react to forces being applied in tension. Whilst the tensile strength of the TIG welded joints represents 66% from that of the parent metal, in the case of FSW butt joints the tensile strength is reaching about 75% in comparison with the tensile strength of the base metal. Because the welding principle is different, also the breaking location is different. That is why the fracture was located at the external limit of the tool shoulder for the joints performed by FSW and in the heat affected zone in the superheating area for the TIG welded joints. Finally, the output data achieved by modelling and experimental results are analysed and discussed.

Key-Words: - FSW, TIG, aluminium alloy, heat transfer, tensile test, simulation.

1 Introduction

The aluminium alloys are using in the aero-spatial industry from the beginning of the last century. In this industrial branch, the basic alloys are 2xxx and 7xxx, but, presently, the 6xxx aluminium alloys present a particular interest not only for researchers but also for the experts of the companies. Troeger and Starked reported that the 6xxx alloys have many advantages such as medium resistance, plasticity, good welding characteristics, corrosion resistance and a low cost. Besides, applying thermal treatments, the 6xxx aluminium alloys are used in many applications (the exterior of the planes fuselages, panels and even in automotive shock absorbers), in the detriment of the 2xxx and 7xxx alloys [9].

On the other hand, in practice there can appear some issues such as the low wear resistance and casting defects [6]). In order to improve the low resistance different methods were applied, including the fusion welding processes as laser and plasma, but the porosities and cracks maintained near the welds. FSW is an alternative procedure which can be used for welding similar or dissimilar materials, but can also involve high plastic deformations of the materials during the solid state joining process. This process produces low distortion, high quality, and low cost welds on aluminium alloys, even those difficult to weld by traditional fusion processes [2].

The present research focussed on the modelling by finite elements of the heat transfer and simulation of the tensile test when applying FSW and TIG welding at the joining of aluminium alloy AA 6082-T6 sheets. Both the numerical and experimental results revealed big differences between the behaviour of the base materials welded by these techniques. A comparative study between numerical and experimental data is made for the both welding variants.

2 Data Input Description

The code source used for simulation and modelling of the welding processes was MSC Marc which is a tool useful for solving a variety of large linear and non-linear structural, thermal, thermo-mechanical problems. In developing the 3D numerical models

of the heat transfer analysis, the following assumptions were taken into account:

- isotropy of the base metal;
- thermo-physical properties of the material depend on the temperature;
- heat conduction within the specimens, free convection between the surfaces of the specimens and the surrounding air and thermal radiation from the top surface of the welded joint are considered in the model;
- the yield point of the material depends on the temperature.

Taking into consideration the material behaviour, large displacements and contact elements presence, the analysis applied was a non linear quasi-static one. The parent material was described by important properties such as:

- Young's modulus, E=6,9·10^{10} N/m^2;
- Poisson'ration, ν=0,33;
- Mass density, ρ=2700 kg/m^3;
- Thermal conductivity, k=174 W/m°C;
- Specific heat, c=935 J/kg°C;
- Thermal expansion coefficient, α=2,4·10^{-5} 1/°C;
- Yield point, σ_c=1,75·10^{8}N/m^2
- Latent heat L=300 kJ/kg between θ_S=550°C and θ_L=585°C.

The model of material behaviour was considered the Johnson-Cook model, as equation (1) describes:

$$\sigma = \left[A + B\left(\bar{\varepsilon}^{pl}\right)^n\right]\left[1 + C\cdot\ln\left(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_o}\right)\right]\left(1-\hat{\theta}^m\right) \qquad (1)$$

where $\hat{\theta}^m$ is given by the relation (2):

$$\hat{\theta}^m \equiv \begin{cases} 0, & \theta < \theta_{room} \\ \dfrac{\theta-\theta_{room}}{\theta_{melt}-\theta_{room}}, & \theta_{room} \le \theta \le \theta_{melt} \\ 1, & \theta > \theta_{melt} \end{cases}$$

$$\dot{\bar{\varepsilon}}^{pl} = \dot{\varepsilon}_o \exp\left[\frac{1}{C}(R-1)\right], \qquad \bar{\sigma} \ge \sigma_o \qquad (2)$$

$\bar{\sigma}$ is the yield stress; $\bar{\varepsilon}^{pl}$ is equivalent plastic strain; $\dot{\bar{\varepsilon}}$ is the current equivalent strain rate, $\dot{\varepsilon}$ is strain rate of material,. $\theta, \theta_{room}, \theta_{melt}$ are, respectively, the current, room, and melting temperatures of the material in absolute scale; σ_o is initial yield stress; A, B, C, n and m from the equation (1) are material parameters with the values from the table 1.

Table 1. Material parameters

Material parameters	Value
A	285 [Mpa]
B	94 [Mpa]
n	0.41
m	1.34
C	0.002
$\dot{\varepsilon}_o$	1
θ_{melt}	588[°C]
$\theta_{transition}$	25[°C]

The accuracy of the numerical results is strongly connected to the accuracy of the data input. The same process data used in the experimental procedures were introduced in the 3D numerical models. The AA6082–T6 aluminium alloy sheets of 5x100x300mm dimensions were welded in the experimental conditions which are fully described in the table 2. No any kind of heat treatment was applied after the welding process.

Table 2. Welding parameters [3]

Welding procedure	Process data
FSW	Tool shoulder diameter, Φ=22mm Cylindrical pin M6, length l=4,8mm Welding speed, v=180mm/min Rotational speed, n=1200rpm
WIG	Filler metal: wire of AlMg5 Inert gas: Alumix–I3(50%Ar+50%He) Current amperage, I=162A Voltage, U=21V, Welding speed, v=24cm/min.

The FSW welding tool geometry, characterized by shape and geometrical dimensions shown in the figure 1, was designed so as to achieve the optimum temperature for a good politicisation of the parent material. The tool shoulder diameter is of 22mm and the tool pin is cylindrical and threaded. The tool was made of X38CrMoV5 tool steel material with hardness of 55sHRC [3].

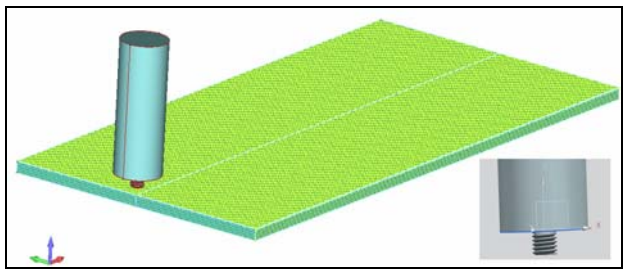

Fig.1. A schematic overview of the FSW process

3 Heat Transfer and Von Mises Stress Modelling

In the FSW process, heat is generated by friction between the tool and the workpiece. The amount of heat conducted into the workpiece determines the weld quality, residual stress and distortion of the joint. The amount of the heat that flows to the tool dictates the life of the tool and the capability of the tool for the joining process [1], [10].

3.1 Heat Transfer and Von Mises Stress in FSW Welded Joints

The complex interactions between a variety of simultaneous thermomechanical processes affect the heating and cooling rates, plastic deformation and flow, dynamic recrystallization phenomena and the mechanical integrity of the joint. The heat and mass transfer depend on material properties as well as welding variables including the rotational and welding speeds of the tool and its geometry [7].

The temperature fields in FSW exhibit certain special features. The peak temperatures are significantly lower than those attained in conventional fusion welding processes. Peak temperatures in the work-piece are attained close to the edge of the tool shoulder and significant spatial gradients of temperature exist in the vicinity of the tool surfaces. Even for a high thermal conductivity material such as aluminium, convective heat transfer is an important mechanism for heat transfer near the tool during FSW [7].

The lack of defects is strongly connected to how the heat transfer is developed in the welded joint. The investigations of AA6082-T6 welded joints have proved that a process temperature of 390…420ºC assures a good quality of the joint. The heat transfer image captured at 50s from the beginning of the welding process and the temperature profile in the cross section of the joint are presented in the figure 2, respectively figure 3.

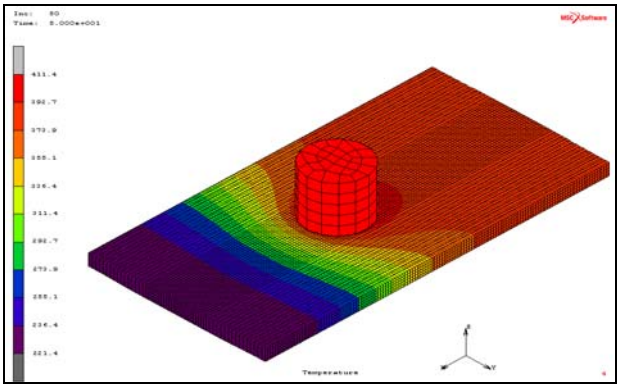

Fig.2. Temperature field in FSW welded joints

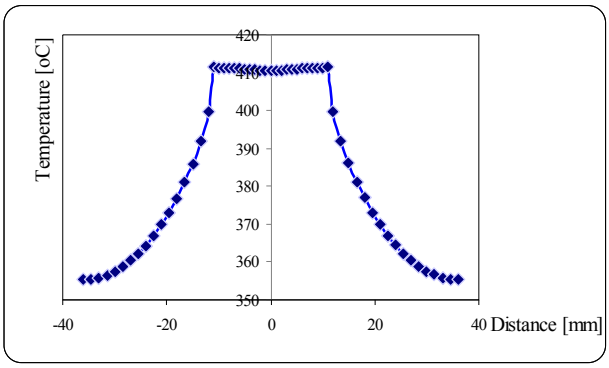

Fig.3. Temperature profile in the cross section of the joint welded by FSW procedure

Due to the particularities of the FSW process, the temperature chart shows a slight temperature asymmetrical distribution in the cross section of the joint. Other information is related to the peak temperature, lower than the melting temperature, which is included in the temperatures range associated with welded joints free from flaws. Any value of process temperature outside this range may lead to imperfections in the joint. If the process temperature is lower, lack of penetration and unconsolidated nugget could occur in the joint. On the other hand, if the process temperature is higher, structural modifications in the thermomechanical affected zone (TMAZ) could have negative effects on the mechanical properties of the joint.

Using the numerical results of temperature field, a thermomechanical analysis could be carried out. Consequently, figure 4 describes the global distribution of Von Mises stress at the moment of 50s from the beginning of the process. Due to the friction phenomenon, caused by the rotation movement of the tool and pressing force required for the penetration of pin into the base material, the highest stress level is achieved in the contact area of the pin with the parent material. Also, in the cooling phase of the joint, increasing the cooling time, the internal stresses increase and Von Mises stress level increases, too.

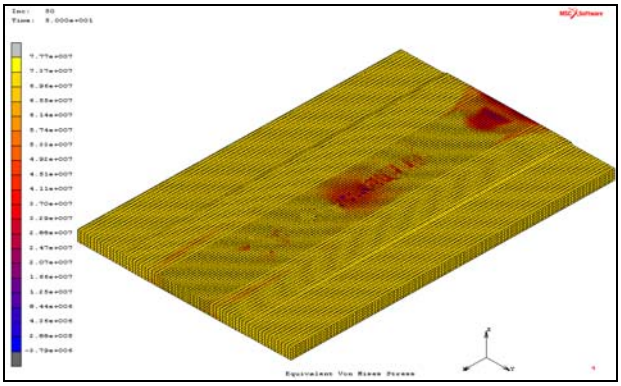

Fig.4. Von Mises stress field in FSW welded joints

3.2 Heat Transfer and Von Misses Stress in WIG Welded Joints

Applying the same analysis method, the heat transfer and Von Mises stress have been numerically investigated in order to simulate the AA6082-T6 behaviour during welding by TIG classical procedure.

Figure 5 presents a typical symmetrical temperature field achieved at fusion welding of similar base metals. Because of the large heat generated during the fusion welding process, the maximum temperature is higher with approximately 200ºC than in the first case. This time, the peak process temperature is about 610 ºC, higher than the melting temperature of the aluminium alloy, and this aspect will have an important influence on the thermomechanical behaviour of the base material, including on the stress level from the welded joint.

All images (Fig.5 to 7), which illustrate the temperature field contour, respectively temperature profile in the cross section of the joint and Von Mises stress field are captured at 50s. Both the temperature and Von Mises stress fields are symmetrical in comparison to those achieved in the joints obtained by FSW process where the existence of advancing and retreating sides of the weld leads to slight differences of the thermomechanical behaviour in these regions [7], [8].

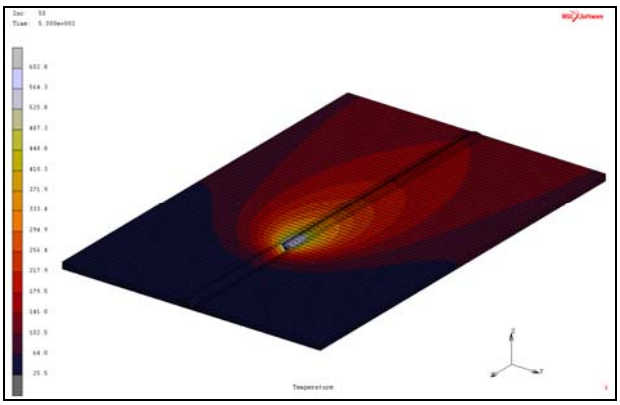

Fig.5. Temperature field in TIG welded joints

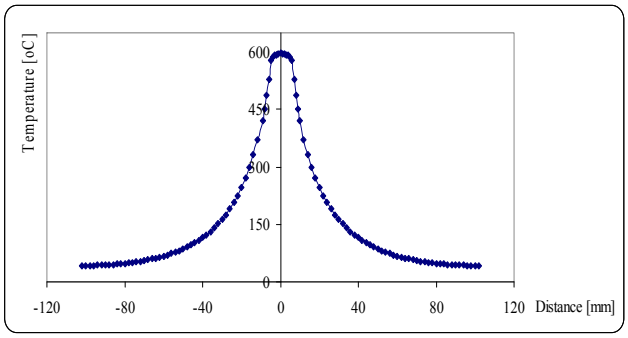

Fig.6. Temperature profile in the cross section of the joint welded by TIG procedure

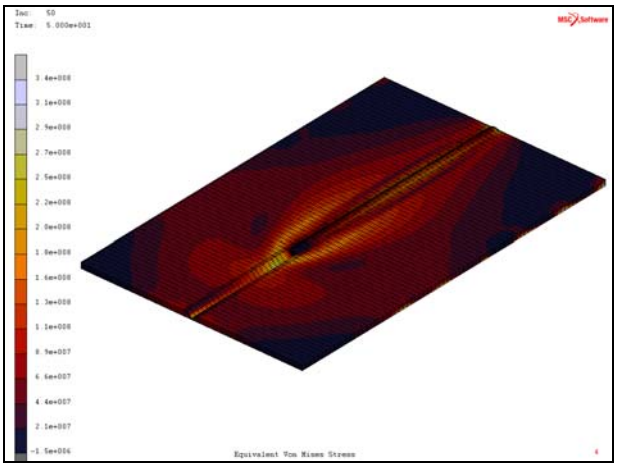

Fig.7. Von Mises stress field in TIG welded joints

4 Tensile Test

It is known that the FSW process assures a great number of advantages and makes it one of the most appreciated welding procedures which could be applied in almost all industry branches. Besides, comparing with TIG procedure, root preparation, filler metal and shielding gas are not required in materials joining by FSW procedure. For a deeper understanding of the welding process influence on the mechanical properties of the joint, a comparative investigation between the tensile test results of FSW and TIG welded joints would provide more information about the thermomechanical behaviour of AA6082-T6 at welding. That's why an experimental and numerical research was conducted and showed different thermomechanical behaviour of the aluminium alloy 6082-T6 at FSW and TIG welding. Firstly, the visual inspection didn't show surface defects such as cracks, pores or lack of penetration in the cross section of the joint.

The geometrical dimensions of the AA6082-T6 welded plates were 5x100x300mm. The specimens were sampled perpendicular on the welding direction, as figure 8 illustrates, both from the joints welded by FSW and TIG and also from the base metal before welding. The geometrical dimensions of the specimens subjected to the tensile test are presented in the figure 9.

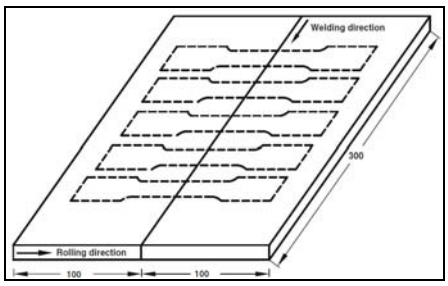

Fig.8. Sampling scheme of specimens

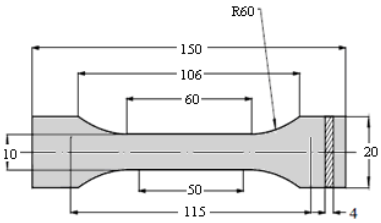

Fig.9. Sample geometrical dimensions

Three-dimensional finite element analysis (FEA), using MSC Marc code, is applied to check the mechanical behavior of AA6082-T6 before welding and after welding by FSW and TIG under tensile loading conditions. The images a, b and c from figure 10 represent the tensile test simulation. As the images show, the fracture was located in different zones of the specimens. For instance, the unwelded specimen of AA6082-T6 was broken in the middle of the sample (Fig.10.a). As regards the specimen sampled from the joint welded by FSW procedure, the rupture occurred in the external part of the weld line, in a transition between welded and unwelded material zone (Fig.10.b), whilst in the sample welded by TIG the initial cracks have occur in the heat affected zone - HAZ (Fig.10.c).

The research has included also an experimental investigation of 6082-T6 aluminium alloy samples subjected to tensile axial loads, similarly to the conditions applied in the simulation. The experimental results validated the 3D numerical model developed and there is a good accuracy of the numerical results, as table 3 shows.

Table 3. Tensile test results

Sample	**Tensile test results** [MPa]	
	Experiment	**FEA**
Base Metal	322	326.6
FSW Joint	243.3 ± 3.5	242.2
TIG Joint	214.93 ± 1.97	217.8

The behaviour of AA6082-T6 before welding and after welding by FSW and TIG procedures is also described by the chart presented in figure 11. The comparative analysis shows that the fusion welding process has a strong influence on the tensile strength which decreases 33% in comparison to that of the base material. If FSW procedure is applied, the tensile strength of the joint decreases 26% from the initial tensile strength. The conclusion is that the mechanical properties of the TIG welded joint are more affected during the fusion welding process and FSW could be a better technical solution for joining if the general conditions related to geometry, design, welding position etc allow it.

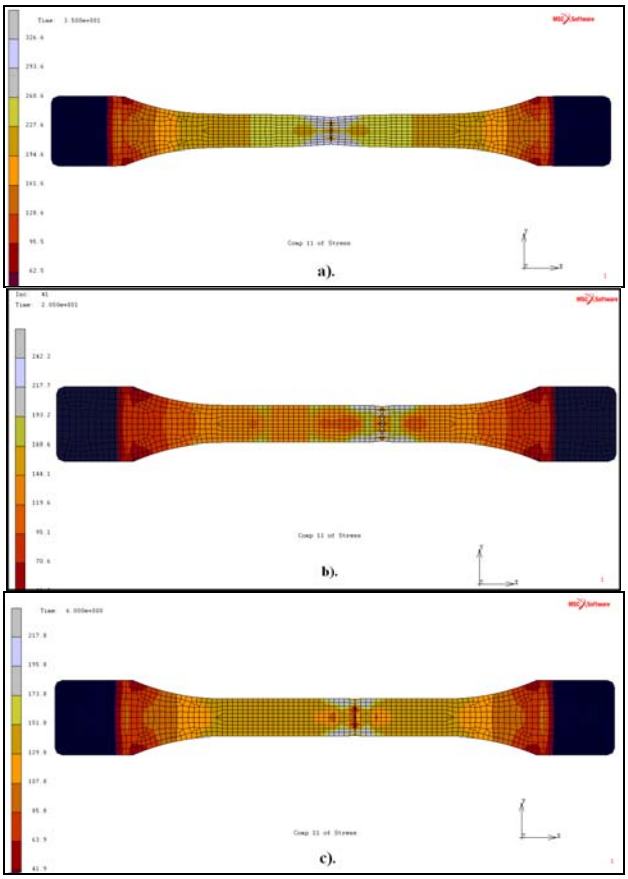

Fig.10. Stress component 11:
a) Base material; b) FSW weld; c) TIG weld

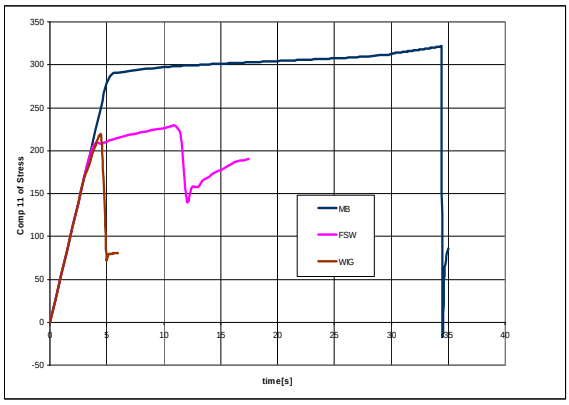

Fig.11. Uniaxial stress curves:
Base material (MB), FSW joint and TIG joint

5 Conclusion

Taking into account the great number of advantages, Friction Stir Welding (FSW) could be a welding ecological alternative to the classical fusion welding procedures. Higher process temperature reached in the fusion welding process, with negative consequences on the metallurgical and mechanical behaviour of the aluminium alloy, makes FSW procedure more attractive from this point of view. Besides, because no filler wire is required then more

reduced weight is achieved and due to the lower heat input required then less distortion occurs in the joint.

The behaviour study of the AA6082-T6 has included a complete numerical analysis of the thermal transfer, Von Mises stress field, tensile test when FSW and TIG procedures were applied for joining. The comparative study, based on the 3D FEA, has revealed the strong influence of the welding process on the material behaviour, especially in the case of the fusion welding process.

The good accuracy of numerical solutions and experimental results validates the 3D model developed by the authors. Hence, FEM is a useful tool in predicting the materials behaviour subjected to the welding process.

Acknowledgement

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