Research on Friction Stir Welding and Tungsten Inert Gas assisted Friction Stir Welding of Copper

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Abstract: - This paper addresses a comparative study on Friction Stir Welding (FSW) and Tungsten Inert Gas (TIG) assisted FSW of copper. Adding an additional heat source, the base materials are preheated and some remarkable advantages are obtained such as: faster and better plasticization of the base material, reduced FSW tool wear and clamping forces, faster welding speed and improved weld quality. The aim of the investigation was to develop two finite element models, which simulate the welding of copper by FSW and TIG assisted FSW procedures, useful to predict the temperature distribution, peak temperature of the process, temperature changes in the cross section of the welded joints. The outcomes of the investigation are compared and analysed for the both welding variants. The numerical models were validated by thermography method.

Key-Words: - Friction Stir Welding, TIG assisted FSW, temperature field, copper.

1 Introduction

FSW is a quite recent innovative method, patented by Thomas Wayne from The Welding Institute - TWI, United Kingdom, which involve high plastic deformations of the materials during the solid state joining process. Welding of copper is usually difficult by conventional fusion welding processes because the copper has the high thermal diffusivity, which is about 10 to 100 times higher than in many steels and nickel alloys. The hear input required is much higher than in almost any other material, and weld speeds are quiet low. To overcome these problems, the FSW which is one of the solid state welding techniques is applied to the joining of copper [9].

The welding variables and the material properties affect the temperature profiles, cooling rates, microstructure and the resulting properties of the welded joint. The temperature fields in FSW exhibit certain special features. The peak temperatures are significantly lower than those attained in conventional fusion welding processes. Furthermore, diffuse heat source in the FSW process and relatively low welding speed often results in low cooling rate in FSW [4], [2].

On the other hand, the patent developed by Kou S. and Cao G. claims a pre-heating system, with a TIG arc welding torch, which extends the range of FSW to harder materials and dissimilar metals joining [3]. The torch preheats the workpiece without supplying any meltable material on the workpiece and the FSW head follows the path of the torch about the workpiece [4]. As FSW has expanded to welding higher strength materials, large process forces and extreme tool wear have become issues [1]. One possible solution is introducing an additional heating source in front of the FSW tool which softens the material and reduces the tool loads [7]. Sinclair et al. reported that preheating the workpiece results in a significant (43%) reduction in the axial force experienced by the tool for a wide range of welding parameter. The flow of the material within the weld nugget was also observed to increase, resulting in a larger weld joint producing stronger welds [7].

Taking into account the aspects described above, the authors combined TIG and FSW procedures in order to make easier the copper welding. Adding an additional heat source, the copper base materials are preheated and some remarkable advantages are obtained such as: faster and better plasticization of the base material reduced FSW tool wear and clamping forces, faster welding speed and improved weld quality. The aim of the investigation was to develop two finite element models, which simulate the welding of copper by FSW and TIG assisted

FSW procedures, useful to predict the temperature distribution, peak temperature of the process, temperature changes in the cross section of the welded joints. The outcomes of the investigation are compared and analysed for the both welding variants. The numerical models were validated by infrared thermography method.

2 Finite Element Modelling (FEM) of FSW and TIG assisted FSW Processes

Generally, the input data and boundary conditions are similar for the both welding variants, excepting the elements type. The geometric model is developed by considering that both the materials are in perfect contact at the interface. Due to the additional heat introduced by the supplementary thermal source in the case of the hybrid welding process, it is expected that the peak temperature of the welding process to be higher in comparison with the classical FSW process.

2.1 Similar Input Data and Boundary Conditions

The code source used for simulation and finite element modelling of the welding processes was MSC Marc which is a software based on finite element method and an instrument useful for solving a variety of large linear and non-linear structural, thermal, thermal-mechanical problems.

The accuracy of the numerical results is strongly connected to the accuracy of the data input. The numerical model was developed taking into account the following aspects:

- the geometrical description of the whole welding system was based on the schematic representation illustrated in the figure 1.
- the geometrical dimensions, in mm, of the copper sheets were 5x50x150;
- the element topology used, HEX 8, is eight nodes and has plasticity, stress stiffening, large deflection and large strain capabilities. 540 elements were generated for the welding tool and 14400 elements for the modelling of the base materials.

A non-uniform mesh pattern is generated: fine mesh is created in the region of the welding tool in order to cover the main regions of the joint – nugget zone, heat affected zone (HAZ) and thermo-mechanically affected zone (TMAZ) – which are strongly affected by the process and less fine mesh in the base materials where the modifications caused by the influence of the process are not so important.

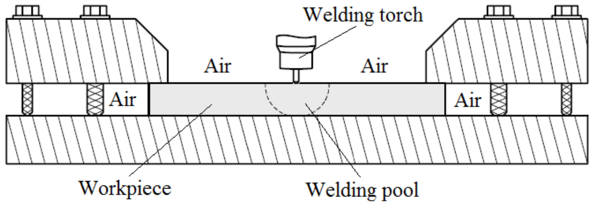

Fig.1. Schematic representation of the welding process

Due to the behaviour of the material, large displacements and contact elements presence, a non linear quasi-static analysis was applied for the assessment of the finite element model. The numerical model developed for the thermo-mechanical field analysis has included the following assumptions:

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

At the beginning of the process, when the initial temperature is 20ºC, the following characteristics of copper were introduced in the both numerical models:

- Young’s modulus, E=1,13·10^{11} N/m^2;
- Poisson’ration, ν=0,3;
- Mass density, ρ=8900 kg/m^3;
- Thermal conductivity, k=375 W/m°C;
- Specific heat, c=390 J/kg°C;
- Coefficient of thermal expansion, α=1,6·10^{-5} 1/°C;
- Yield point, σ_c=1,75·10^8 N/m^2.

A SOLID 3D element “coupled” which allows both thermal and mechanical properties description was considered in the modelling. In the finite element analysis of the welding processes, the model of the material behaviour is an elasto-plastic Von Mises which is a bilinear model with tangent modulus different from zero. Newton-Raphson procedure was applied to the numerical integration, where the rigidity matrix was evaluated for every loading step and iteration.

The tool was defined as body deformable and its movement - along the longitudinal axis of the joint - was simulated by defining the time functions as a sum of triangle functions (Fig.2).

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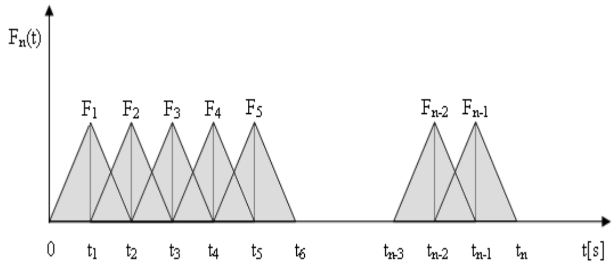

Fig.2. Time functions simulating the welding torch movement [5]

The process parameters were kept constant whilst the welding source moved continuously, heating and plasticizing new regions in front of it. The succession of the triangle functions simulates the welding process starting from the initial moment $t=0$ until the final moment $t=t_n$.

The dimensional characteristics of the welding tool, introduced in the model are presented below:

- tool shoulder diameter, $d_{shoulder}$=25mm;
- pin diameter, d_{pin}= 5,5mm;
- pin length, l_{pin}=4,8 mm.

The friction, that occurs between the welding tool and the workpiece coefficient, is characterized by the friction coefficient (μ) whose value is 0,25.

2.2 FEM of FSW Process

The authors developed an original 3D model, based on a coupled thermomechanical modelling, in which the thermal flux or heat flux is kept constant at the contact interface between the tool shoulder and workpiece. The equation that describes the thermal flux is given by the following mathematical relation:

$$q(r) = \frac{3Q \cdot r}{2\pi \cdot r_0^3} \quad (1)$$

where $r \le r_0$, r_0 is the radius of the tool shoulder and Q represents the whole heat generated during the welding process.

The heat, Q, developed during the welding process depends on many parameters as the equation (2) shows:

$$Q = \frac{\pi \cdot \omega \cdot \mu \cdot F \cdot \left(r_0^2 + r_0 \cdot r_i + r_i^2\right)}{45 \cdot \left(r_0 + r_i\right)} \quad (2)$$

In the relation above ω is the rotational speed of the welding tool, μ - friction coefficient between the welding torch and the base material, F - pressing force and r_i - pin radius.

A significant benefit of FSW is that it has significantly fewer processing parameters to control, comparing with classical fusion welding processes. The main process parameters which have an important influence on the welding process and the geometrical dimensions of the weld are:

- rotational speed, ω=1000 rpm;
- welding speed, v=80 mm/min;
- pressing force, F=25kN;
- pin angle, α=2,5º.

2.3 FEM of TIG assisted FSW Process

The supplementary heat source, having preheating effect, is often used in the welding processes. The amount of heat conducted into the workpiece determines the quality of the weld, residual stress and distortion of the workpiece. Applying the additional thermal source TIG, the amount of the heat generated during the welding process may be calculated with the following relation:

$$Q = Q_{FSW} + Q_{TIG} \quad (3)$$

where Q_{FSW} represents the heat developed by FSW procedure and Q_{TIG} is the heat generated during the welding by TIG method.

The main parameters, of TIG assisted FSW process, are connected to the geometrical characteristics of FSW tool, FSW process parameters and TIG process parameters [11].

- Geometrical characteristics of FSW tool
  - tool shoulder diameter, $d_{shoulder}$=25mm;
  - pin diameter, d_{pin}= 5,5mm;
  - pin length, l_{pin}=4,8 mm.
- FSW process parameters:
  - rotational speed, ω=1000 rpm;
  - welding speed, v=80 mm/min;
  - pressing force, F=25kN;
  - pin angle, α=2,5º.
- TIG process parameters:
  - welding speed, v=80 mm/min;
  - welding amperage, I=230A;
  - voltage, U=20V.

3 Results and Discussions

The heat transfer process is one of the most important aspects in the welding study. A good understanding of the heat transfer process in the workpiece can be helpful in predicting the thermal cycles and structural modifications in the base materials. In this section, numerical and experimental analysis is made both for the FSW variant and TIG assisted FSW procedures.

The measurement method that was applied to achieve the profile of the temperature, during the welding process, was thermography method which is a non-destructive evaluation method based on the infrared radiation.

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3.1 Thermal Analysis at FSW Welding

Figure 3 illustrates the image of the temperature field captured at time of 50s. The heat source used for modelling was described by the friction between the material and the tool, including the pin influence on heating base material.

In the friction stir welding (FSW) process, heat is generated by friction between the tool and the workpiece. This heat flows into the workpiece as well as the tool. In modelling of the temperature history, the moving heat sources of the shoulder and the probe are represented as moving the heat generation of the nodes in each computational time step. The analysis of the numerical results has revealed a peak temperature of 645ºC which was recorded in the shoulder tool area and a process average temperature of 524ºC.

The continuous movement of the welding tool, along the joining direction, and the simultaneous heat dissipation by conduction make possible the heating of new regions in front of the torch. The temperature gradient is high around the welding zone and seriously changes the materials properties. The isotherms are shown and visible in the capture presented in the figure 4.

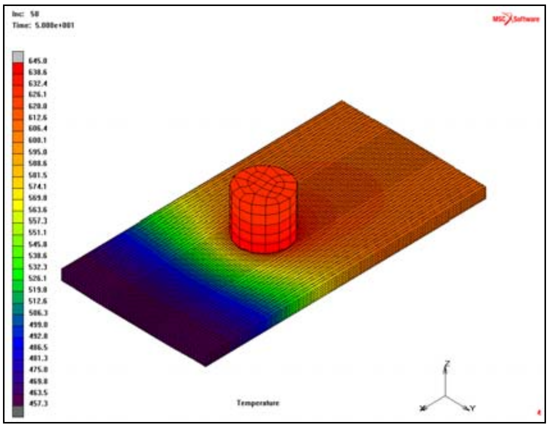

Fig.3. Temperature field at the moment t=50s

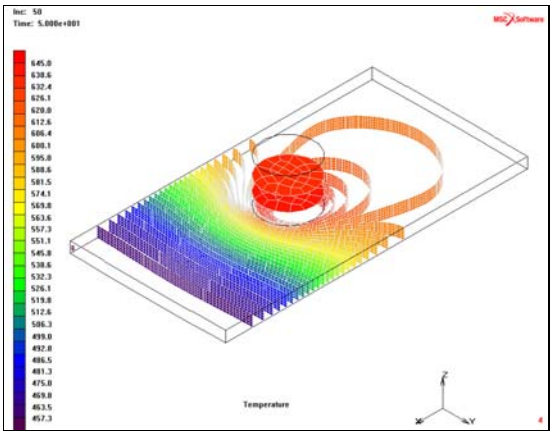

Fig.4. Isotherms at the moment t=50s

The amount of heat conducted into the workpiece determines the quality of the weld, residual stress field and distortion level of the workpiece. The amount of the heat that flows to the tool, considered as maximum on the starting plunging phase of the process, dictates the life of the tool and the capability of the tool for the joining process [10]. The temperature profile in the cross section of the joint is relevant for the mode in which the heat transfer is performed during FSW welding, as figure 5 shows. After the complete penetration of the welding tool the peak temperature is registered at the shoulder – workpiece interface because of the supplementary heat developed by friction between shoulder and probe. The peak temperatures are significantly lower than those attained in conventional fusion welding processes.

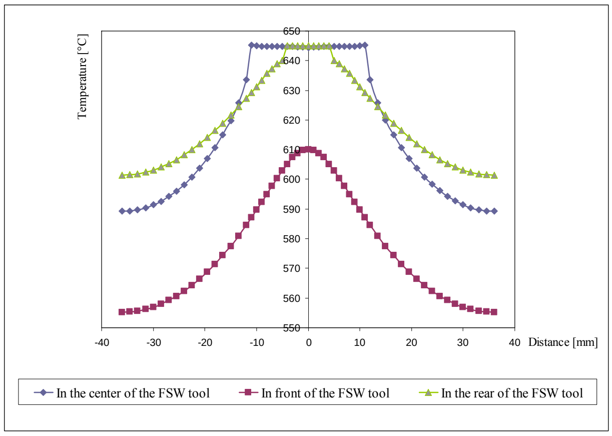

Fig.5. Temperature profile in the cross section of the welded joint

A high-speed and high-sensitivity thermographic infrared (IR) imaging system was used for non-destructive evaluation of temperature evolution. The device was a thermal camera in infrared type FLIR Systems ThermoVision A20M which was fixed on the welding torch.

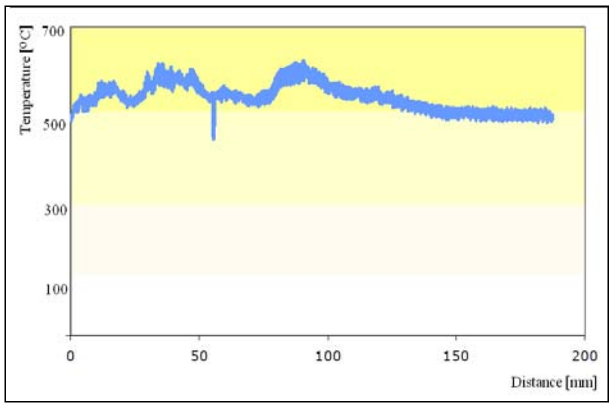

Fig.6. Experimental measurement of temperature during FSW process

The average value of temperature is 520ºC whilst the maximum one is around 630ºC. The numerical and experimental results match, which means that the finite element model developed is right and it may be used to predict the temperature field, size of heat affected zone (HAZ) and thermal cycles.

3.2 Thermal Analysis at TIG assisted FSW

The reason to add an additional heat source in front of the FSW tool is to reduce the heat input required from the tool and thus the process loads [7]. Fixing a TIG arc-welding torch, FSW tool wear is reduced and the FSW procedure can be extended to harder materials and dissimilar metals joining [7].

The image of the temperature field, captured at the moment of 50s, shows the preheating effect of the thermal source - TIG coupled with the effect of the conduction heat transfer produced by the FSW tool. More significantly is the image of the isotherms registered at the same moment and illustrated in the figure 8. Due to the additional thermal source, the peak temperature achieved in this case is about 745ºC, about 100ºC higher than the maximum temperature acquired in the first case.

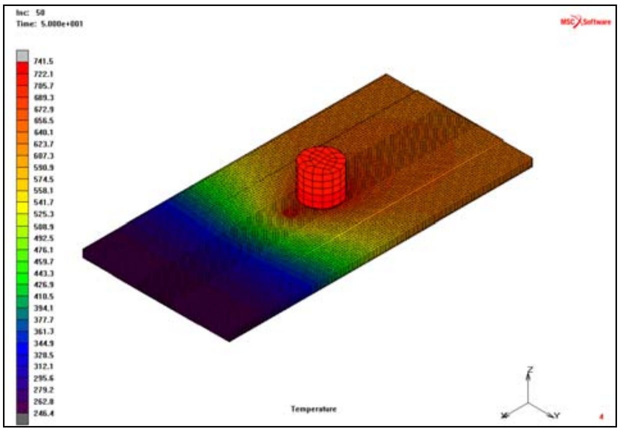

Fig.7. Temperature field at the moment t=50s

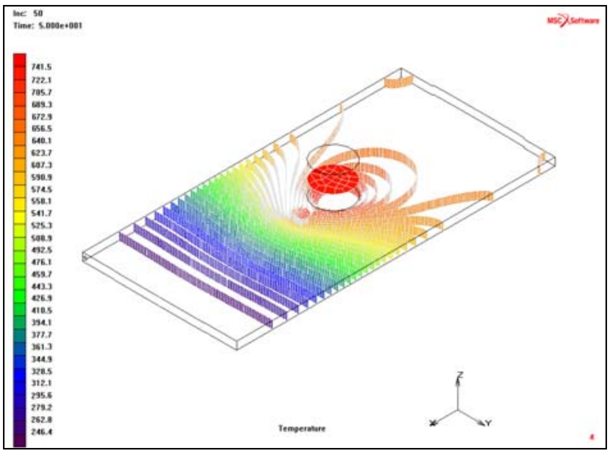

Fig.8. Isotherms at the moment t=50s

The charts presented in the figures 9 and 10 represent the temperatures distribution graphs in the cross section of the welded joint, both in the influence region of the FSW tool and in the action area of the TIG thermal source. As we expected the peak temperature is reached in the middle of each tool/source.

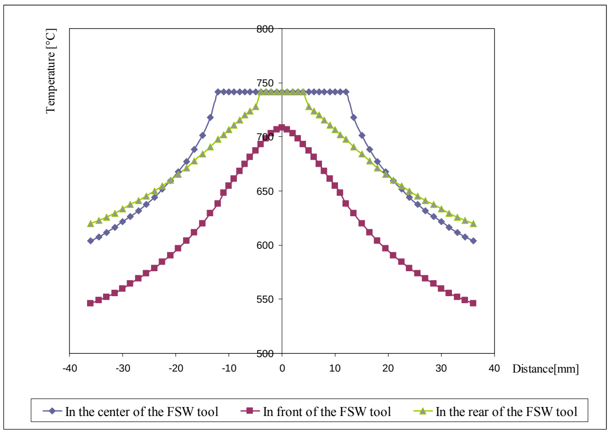

Fig.9. Temperature variation in the cross section of the welded joint (in the area of the FSW tool)

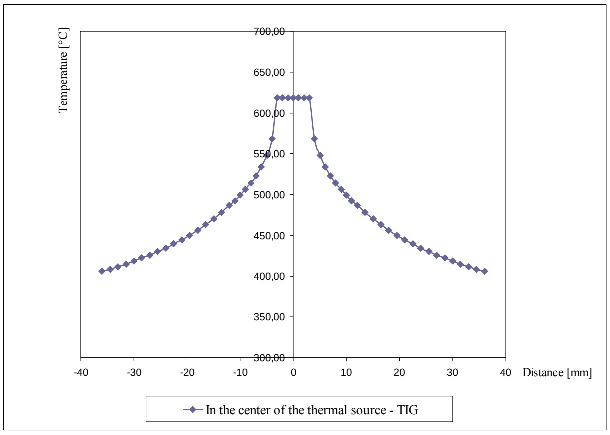

Fig.10. Temperature variation in the cross section of the joint (in the area of the thermal source TIG)

Based on the temperature measurements, acquired with the same high-sensitivity thermographic infrared imaging system, a diagram was plotted (Fig.11). The thermogram describes the heat history registered along the joint line during the welding process of copper. The experimental data prove that the model developed can be an useful instrument in predicting the peak temperature, extension of the regions affected by the welding even in the case of the combined and complex joining process, as TIG assisted FSW is.

The process maximum temperature of 730ºC was obtained in the quasi-stationary phase of the joining process.

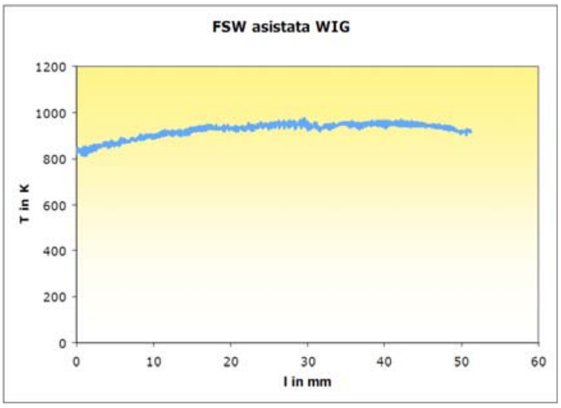

Fig.11. Experimental measurement of temperature during TIG assisted FSW process

4 Conclusion

Finite element analysis is a useful tool in predicting the materials behaviour subjected to the welding process. Thermal, mechanical and metallurgical modifications could be predicted using this kind of analysis.

The investigation aim was to compare the copper behaviour, from the thermal point of view, when FSW or TIG assisted FSW procedure was applied. The numerical data obtained by FEA were validated by experimental measurements achieved through the thermography method. Due to the additional thermal source, both the finite element analysis and the experimental method revealed that the peak temperature reached in the case of the hybrid welding is around 100ºC higher than the maximum temperature achieved in the first welding variant, even if the welding speed was upper in the TIG assisted FSW variant. That can be explained by the additional heat generated by the thermal source which develops a preheating effect.

It is well known that the weld quality depends on the heat amount generated by the welding source(s). In order to avoid the flaws occurrence, heat flow should be high enough to maintain a maximum temperature of the process around 70 ... 80% of the melting temperature of the base metal.

Acknowledgement

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