Finite element analysis of thermal distributions in dissimilar friction stir welding of copper and aluminum alloy

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Keywords

Dissimilar FSW, FEA, overlay, Abaqus/Cae

Introduction

FSW is a process that can be applied to welding dissimilar materials. There have been conducted several international studies in which FSW welding of aluminum alloys with copper alloys has been analyzed [1-4].

In the case of joining dissimilar materials it is desirable that the two base materials have physical characteristics as close as possible. For FSW welding the plasticizing temperature, thermal expansion coefficient and thermal conductivity are especially important. A different thermal conductivity of the two base materials results in uneven heating of these two materials. Aluminum and copper have partial mutual weldability in solid state and form intermetallic compounds. As such, welding by melting is difficult, leading to the research of the Al-Cu joint by FSW.

Unlike FSW butt welding, where the line of the welding surfaces is vertical, in the case of overlap welding the line of the welding surfaces is horizontal, which causes a totally different flow of the material compared with butt welding.

Simulating the joining process using friction stir welding can lead to avoiding experimentation periods which can be long and costly. Simulation of the FSW process is a complex problem because it involves the interaction of thermal and mechanical phenomena, and the quality of the joint depends on many factors.

Most experimental and simulation research refers to the Friction Stir Welding of aluminum alloys. Simulation of the FSW joint of Al-Copper dissimilar materials is less researched by simulation.

Simulation of the FSW process can be accomplished by 3 methods: Arbitrary Lagrangian Eulerian method (ALE) [5,6,7], Lagrangian incremental method and Coupled Eulerian Lagrangian method (CEL) [8].

This work presents the development of a numerical tool. A Coupled Eulerian Lagrangian (CEL) formulation is implemented in Abaqus/cae software to simulate the Friction Stir Welding (FSW) process. Thus, we will describe the main stages necessary for the realization of the model (geometry, material, interactions, limit conditions), the mode of meshing and validation of the model using the temperature distribution in the parts.

Model descriptions

The geometry used in the simulation is shown in Fig. 1. The specimens are 80x80 mm2 in size and are overlapping 60 mm in length. The welding tool has a shoulder diameter of 20 mm, the pin is conical and smooth with a length of 3.85 mm. The tools are considered to be rigid elements and have been assigned reference nodes, and the parts are deformable.

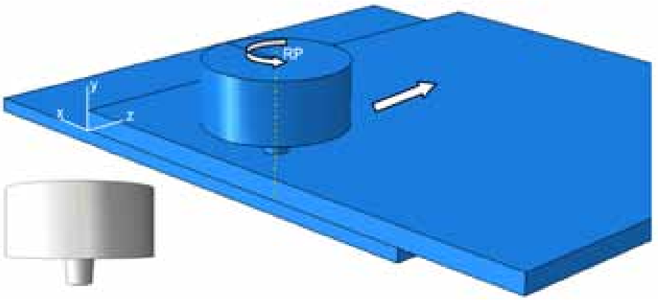

Figure 1. FSW model and 3D representation of the featured tool pin.

The specimen in contact with the tool is Al alloy, AA 6082 and has a thickness of 3 mm, and the bottom specimen is made of Cu and has a thickness of 2 mm.

In the FSW simulation, the behaviour of the material is elastic-viscous-plastic.

The materials used in this study is the Aluminum alloy (AA 6082) and copper (Cu 99). In this work, material plasticity is governed by Johnson-Cook model [9]:

$$\bar{\sigma} = [A + B \cdot (\bar{\varepsilon}^{pl})^n]\left[1 + C \cdot \ln\left(\frac{\dot{\bar{\varepsilon}}_{pl}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_{ref}}{T_{melt} - T_{ref}}\right)^m\right] \tag{1}$$

with: $\bar{\varepsilon}^{pl}$ - the efective plastic strain; $\dot{\bar{\varepsilon}}_{pl}$ - is the effective plastic strain rate; $\dot{\varepsilon}_0$ - is the normalizing strain rate; *n*, and *m* are material constants; *C* represents strain rate sensitivity; T_{ref} is the temperature at which we determine the parameters *A*, *B*, *n*; T_{melt} is the material's solidification temperature.

Thermal and mechanical parameters of AA 6082 and Cu 99 that were used in this analysis are shown in Table 2, were taken from references [10, 11].

The Johnson Cook law constants for these materials were taken from the literature.

Table 1. Constants for Johnson-Cook material model [10,11]

Material	T_{top} [^{o}C]	T_{ref} [^{o}C]	A [MPa]	B [MPa]	C	n	m
AA 6082	645	22	285	94	0.002	0.41	1.34
Cu 99	1082	22	90	292	0.025	0.31	1.09

Parameters entered into the Abaqus software for material definition are summarized in Table 2. To these are added the Johnson-Cook constants with the values shown in Table 1.

Table 2. Properties of workpiece material

Material	Measuring unit	AA 6082	Cu 99
Density	Kg/mm^3	$2.7\cdot10^{-9}$	$8.9129\cdot10^{-9}$
Modulus of elasticity	MPa	69000	117210
Poisson ratio	-	0.32	0.32
Thermal Conductivity	W/m· ºC	174	388
Specific Heat Capacity	J·106/Kg· ºC	899,000,000	385,000,000

The coefficient of friction is $\mu = 0.3$ value that was adopted after an analysis. The contact between the tool and deformable parts is a general contact, in which the tangential behaviour is described by a friction law and the normal behaviour is described by a hard contact which allows the parts to separate after contact.

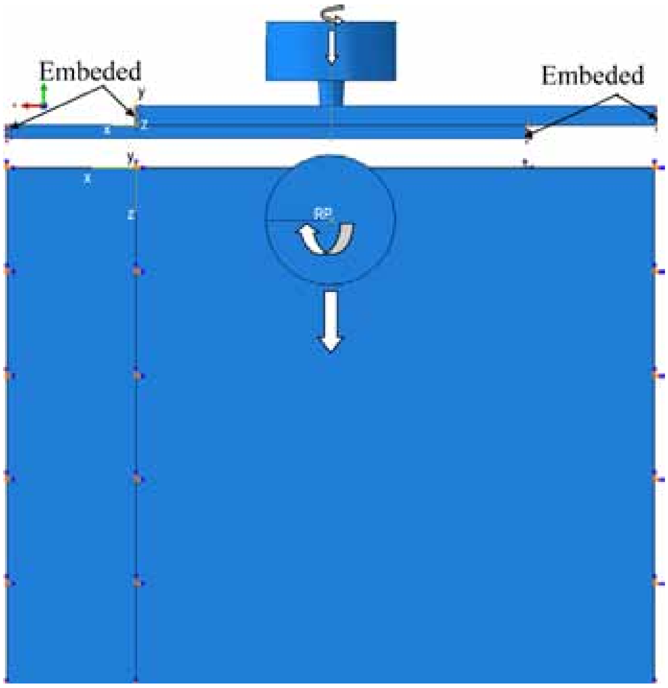

Figure 2. Boundray condition.

The simulation was carried out in two stages: stage 1 - penetration phase, stage 2 - feed phase. Thus, the pieces are embedded, Fig. 2, and the work tool has translational motion on Ox and rotation on the Oy axis. The parts are embedded on the side surfaces. In the penetration phase the tool advance is w = 60mm / min, and the speed is n = 1200rot / min, and in the feed stage the tool advance is 100mm / min and the speed is n = 1200rot / m, clockwise.

The meshing technique using the Coupled Eulerian Lagrangian (CEL) method uses the two Eulerian and Lagrangian methods in the same analysis. The main advantage of this method is that you can eliminate meshing problems when running simulations involving extreme deformations.

This type of method has a number of advantages over the ALE approach:

- It is possible to predict the distribution of the material through the welded body and the formation of gaps while eliminating the distortion of the meshing.
- It is possible to use complex behavioural laws and define the contact behaviour between the constituents of the analyzed system.

Taking into account the above, at this stage the developed model will be meshed using the Coupled Eulerian Lagrangian (CEL) technique.

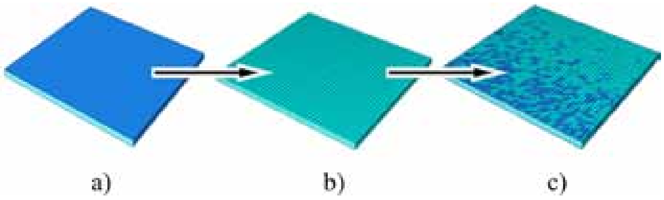

Figure 3. Representation of the Coupled Eulerian-Lagrangian model: a) Lagrangian body; b) Eulerian body; c) Coupled Eulerian-Lagrangian.

The Eulerian body is coupled to the Lagrangian body through contact interaction, fig. 3. Thus, the work tool is a Lagrangian body, and the pieces are attached to Eulerian domains.

The implementation of the Eulerian body in Abaqus / Explicit is based on the fluid volume method. In this method, the material is tracked as flowing through the meshed network by calculating the Eulerian Volume Fraction (EVF) in each element. By definition, if a material completely fills an element, the volume fraction is equal to 1; if the material is not present at all in one element, the volume fraction is zero.

The number of elements in which the pieces are meshed is limited by the calculation time that increases in proportion to the number of elements. Being a 3D simulation, the meshing of the pieces must be made in such a way that the calculation time is reasonable, but the number of elements is sufficient to give the output parameters as close as possible to reality. For this analysis, there are used 4800 thermally coupled EC3D8RT elements, with 8 nodes and 4 degrees of freedom in each node.

The simulation was done using Abaqus / Cae software v.14.1 on an Intel, QUAD Core CPU, 2.66GHz. The memory is 3 Gb RAM, and the operating system is Windows XP, 32 bits. The calculation time was approximately 10 days.

Results and discussion

Experimental results. During the welding process, the temperatures in the welded parts were measured using a high-speed and high-sensitivity thermographic infrared camera (ThermoVisionTM A40 M), having the field of temperature measurement between -40^{o}C and 2000^{o}C. Measurements were made on the joint line at a distance of 1 [mm] behind the welding tool shoulder, Fig. 4, measured temperature being the average value behind the tool shoulder.

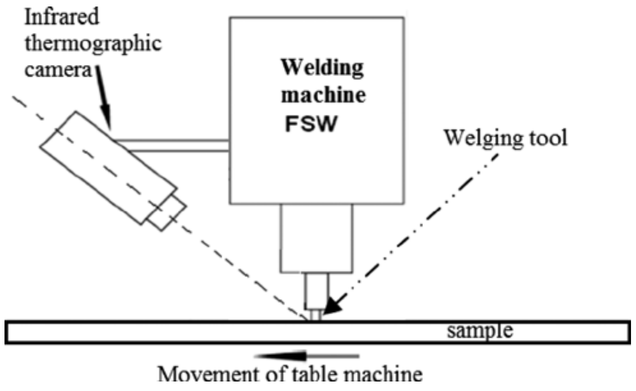

Figure 4. Temperature measurement using a high-speed and high-sensitivity thermographic infrared camera,

Evolution diagram of temperature during FSW welding process for the two experimental cases is represented in Fig. 5.

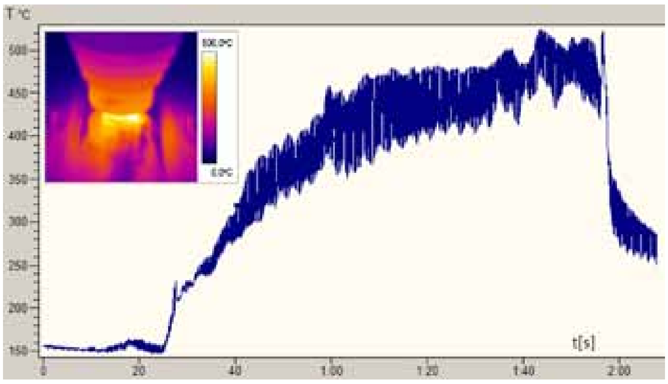

Figure 5. Experimental measurement of temperature during FSW process.

Numerical results. The validation of the FE model was accomplished by comparing the temperature values obtained by the FE simulation with those measured experimentally.

Thus, the evolution of temperature in the plunge phase and in the feed phase was analysed. During the plunge phase the temperature evolution was analysed according to the tool advance.

The temperature distribution at the end of the plunge phase is shown in Fig. 6.

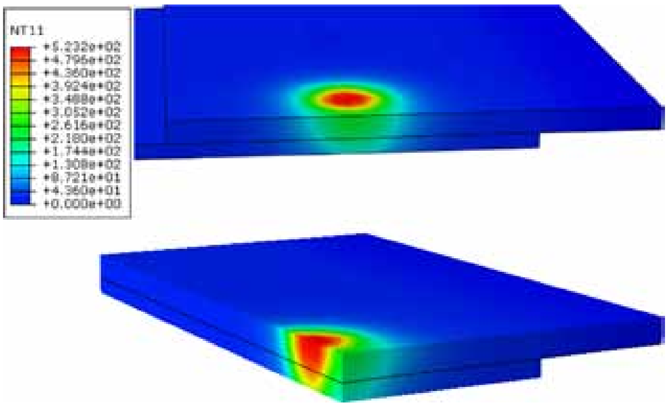

Figure 6. Temperature distribution at the end of the plunge phase.

In Fig. 7 it is observed that, initially, aluminum heats up faster, resulting that at the end of the plunge phase the two materials have close temperature values (578°C aluminium and 615°C copper).

The evolution of temperature in the nugget zone at the top part of the plate made of aluminum alloy and in the bottom part made of copper is shown in Fig. 8.

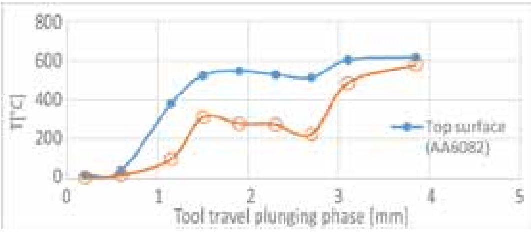

Figure 7. Evolution of temperature according to the tool movement

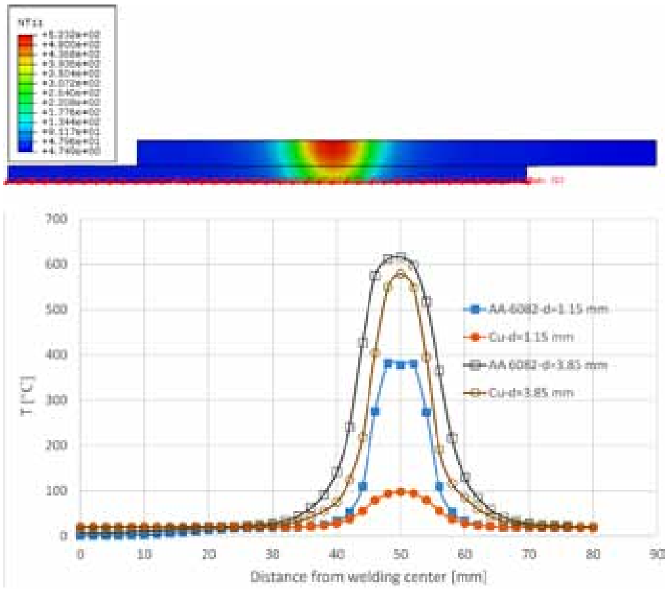

Figure 8. Evolution of temperature according to the tool movement in the nugget zone.

It can be noticed that when the tool moved by 1.15 mm, the two materials heated differently, and at the end of the course (at 3.85 mm) the temperatures were comparable. The maximum temperature is obtained in the nugget zone.

Conclusion

Thermal distributions in dissimilar friction stir welding of aluminum and copper plates have been studied experimentally and using finite element CEL model.

The study results showed that the values of temperatures obtained by simulation are comparable to the experimental ones. In the plunge phase, the two materials initially heat up differently, and at the end, when the tool pin penetrates the Cu piece too, the temperature is uniform. The parts are heated mainly in the nugget zone and in the tool shoulder zone. The model showed that the peak temperature of the workpiece was high, 615°C, close to the melting temperature.

This FE model will be used to optimize the parameters of the FSW process.

Acknowledgements

This work was accomplished within the “Partnerships in priority areas – PN II” program, implemented with the support of MEN-UEFSCDI, project no. PN II–PT–PCCA–2013–4–185.

References

[1]. A. Jawdat Al-Jarrah, Surface Morphology and Mechanical Properties of Aluminum-Copper Joints Welded by Friction Stir Welding, Contemp. Eng. Sci. 7 (2014) 219 – 230

[2]. X.-W.Li, D.-T.Zhang, C. Qiu, W.Zhang, Microstructure and mechanical properties of dissimilar pure copper/1350 aluminum alloy butt joints by friction stir welding, Trans. Nonf. Met.Soc. of China 22 (2012) 1298-1306

[3]. O. Oluwatoyin, T.Ewuola, E. Akinlabi, M. D. Madyira, Effect of Plunge Depth on Weld Integrity of Friction Stir Welds of Dissimilar Aluminium and Copper, Proceedings of the World Congress on Engineering (2016) Vol II WCE 2016, London

[4]. V.C Sinha, S.Kundu S.Chatterjee, Microstructure and mechanical properties of similar and dissimilar joints of aluminium alloy and pure copper by friction stir welding, Persp. in Sci. (2016) 8, 543-546

[5]. X. Zhou, W.Pan, D. MacKenzie, Identifying friction stir welding process parameters through coupled numerical and experimental analysis, Int. J. of Pres. Vess. and Pip. 108-109, (2013), 2-6

[6]. A. Rajasekar, E.P Shanmugam. Finite Element Analysis of Friction Stir Welding of Copper and 6063 aluminium Alloy, Int. J. of Innov. Res. in Sci., Eng. and Tech. (2015) 4 13

[7]. H. Pashazadeh, A.Masoumi, J.Teimournezhad, A 3D numerical model to investigate mechanical, thermal and material flow characteristics in friction stir welding of copper sheets, Int. J. of Aut. Eng., (2013) 3

[8]. D. Jacquin, B. Meesterb, A. Simarb, D. Deloisonc, F. Montheilleta, C. Desrayauda, A simple Eulerian thermomechanical modeling of friction stir welding, J. of Mat. Proces.Techn. (2011) 57–65

[9]. G.R. Johnson, W.H. Cook, A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures, 7th International Symposium on Ballistics, Netherlands (1983) 541-547.

[10]. S. Mandal, J.Rice, G.Hou, K.M.Williamson, A.A. Elmustafa, Modeling and Simulation of a Donor Material Concept to Reduce Tool Wear in Friction Stir Welding of High-Strength Materials, J. of Mat. Engi. and Perf. (2013) 22, 1558–1564

[11]. D. Birsan, E Scutelnicu, D. Visan, Behaviour Simulation of Aluminium Alloy 6082-T6 during Friction Stir Welding and Tungsten Inert Gas Welding, (2011) Proceedings of the 4th International Conference on Manufacturing Engineering, Quality and Production Systems