Numerical Simulation of the Friction Stir Welding Process Using Coupled Eulerian Lagrangian Method

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Abstract. Friction Stir Welding (FSW) is a solid state joining process that relies on frictional heating and plastic deformation realized at the interaction between a non-consumable welding tool that rotates on the contact surfaces of the combined parts. The experiments are often time consuming and costly. To overcome these problems, numerical analysis has frequently been used in last years. Several simplified numerical models were designed to elucidate various aspects of the complex thermo-mechanical phenomena associated with FSW. This research investigates a thermo-mechanical finite element model based on Coupled Eulerian Lagrangian method to simulate the friction stir welding of the AA 6082-T6 alloy. Abaqus/cae software is used in order to simulate the welding stage of the Friction Stir Welding process. This paper presents the steps of the numerical simulation using the finite elements method, in order to evaluate the boundary conditions of the model and the geometry of the tools by using the Coupled Eulerian Lagrangian method.

1. Introduction

Friction stir welding (FSW) is a solid state welding, which is recognized as a better process for joining similar and dissimilar metals and alloys with different physical, chemical, and mechanical properties [1]. Friction stir welding is a complex process which involves interaction of thermal and mechanical phenomena: excessive material deformation around the pin tool accompanied by a large heat flow.

Finite element modelling (FEM) of the FSW process leads to a better understanding of the effect of the process parameters on the welding process and the weld seam properties. Nowadays, FSW finite element models can be classified into three types: thermal, thermo-mechanical non-flow base, and thermo-mechanical flow-based models [2]. In flow-based models, traditional Lagrangian elements become highly distorted and results may lose accuracy. In order to avoid high mesh distortion, several modelling techniques are often used: adaptive re-meshing and Arbitrary Lagrangian Eulerian (ALE). Flow-based models are developed using computational fluid dynamics (CFD). Among the main drawbacks in CFD simulations is its inability to include material hardening as it only considered rigid-viscoplastic material behaviour [3]. Flow-based models are also developed using Coupled Eulerian
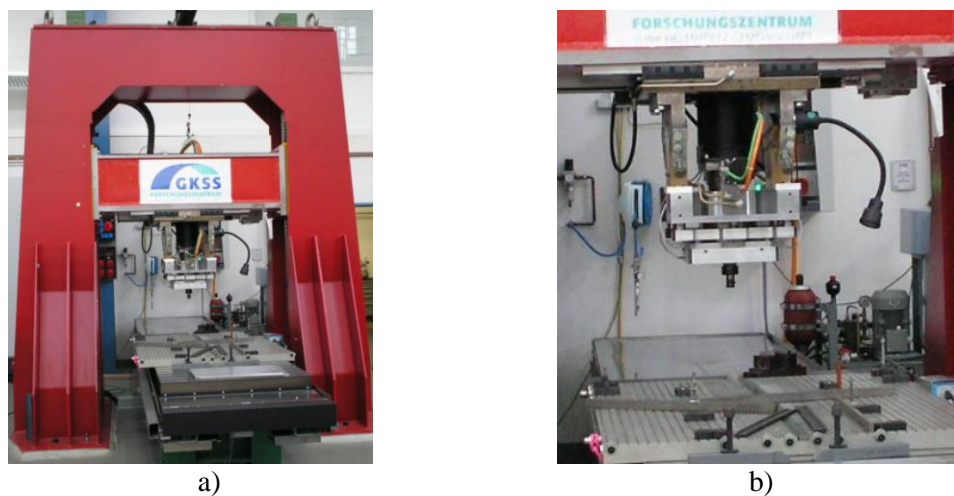
Lagrangian method. This analysis technique combines two approaches, Lagrangian and Eulerian: the tool steel is modelled as rigid isothermal Lagrangian body, while the workpiece is modelled using Eulerian formulation [2]. The interaction behaviour between the two is modelled by contact definition.

This paper presents the steps to achieve a FE model of the FSW process in the ABAQUS/Explicit software, using the Coupled Eulerian-Lagrangian formulation (CEL), the Johnson-Cook constitutive equation for the material deformation, and Coulomb's law of friction.

2. Experimental procedure

The experiments were performed on a portal FSW welding machine that presents a very high stiffness (Fig.1). This machine can provide a maximum force of 45 kN in the vertical axis and 10 kN in the horizontal axis (axis of welder).

| a) | b) |

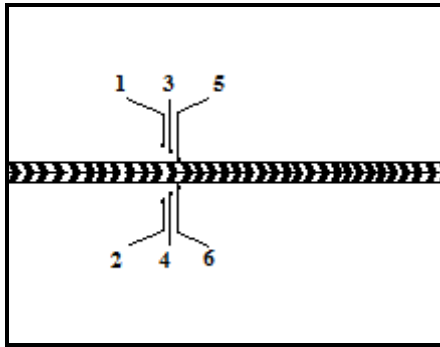**Figure. 1.** The welding machine: a) general overview; b) work area

The samples obtained by welding process are butt joints between two plates, where the dimensions are 65 x 60 [mm^2] and the thickness is 5 [mm]. The material used is an aluminium alloy AL 6082 T6, whose chemical composition is shown in Table 1. The aluminium alloys from 6XXX class are often found in structures, or elements of structures, subjected to fatigue [4].

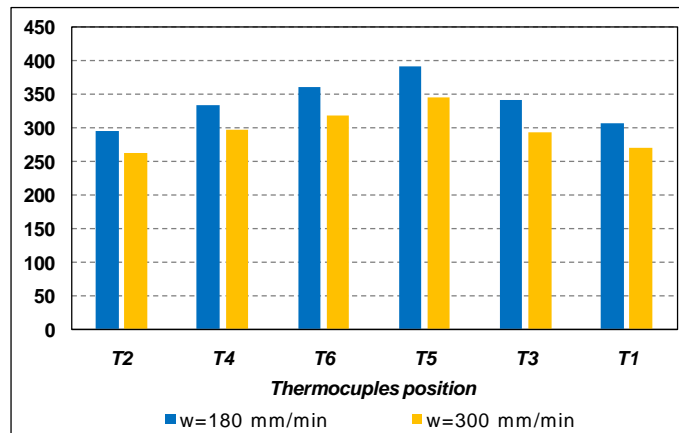**Table 1.** The chemical composition of the alloy AA 6082

Element	Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr
%	0.7 - 0.13	0.5	0.1	0.4 – 1.0	0.6 - 1.2	0.2	0.1	0.25

To achieve the welding seam, we have used a pin with right shoulder and grooves, where the diameter of the shoulder is 15 mm and the threaded pin is M5. The length of the threaded part of the pin is 4.5 [mm]. The values of the process parameters were the following: (i) the rotation speed of the pin: 1200 [rpm] (rotation per minute), (ii) feed rate: 180 [mm / min] and 300 mm / min respectively.

During the welding process, the temperatures in the welded parts were measured using thermocouples, disposed symmetrically to the line of the welding seam (Fig. 2), as follows: thermocouples 1 and 2 are positioned at 20 mm from the welding seam, thermocouples 3 and 4 are positioned at 15 mm from the welding seam and thermocouples 5 and 6 are positioned at 10 mm from the welding seam. The maximum values of the temperature measured by the thermocouples during the welding process are shown in Fig. 3.

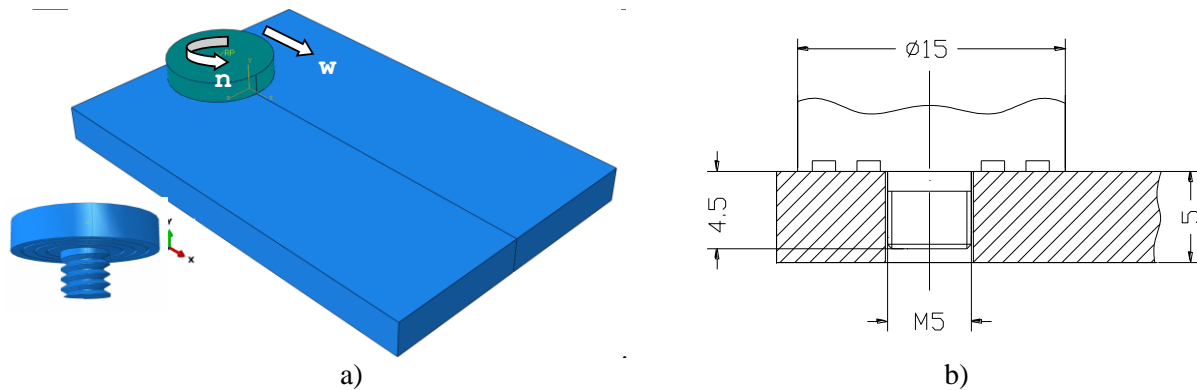**Figure 2.** The spatial position of the thermocouples on the sample.

Figure 3. Maximum temperatures measured by thermocouples during FSW process.

3. Numerical procedure

Finite element modelling of the friction stir welding process is a very complex and complicated procedure because it involves interaction of thermal and mechanical phenomena: excessive deformation accompanied with large amount of plastic straining and heat.

In this paper we focus on the numerical simulation of the process, rather than the experimental characterization. The numerical model developed (geometry of the parts and the values of the process parameters), Fig. 4, corresponds to the experimental conditions during the welding process. The dimensions of workpiece are 65 mm in length, 60 mm in width, and 5 mm in thickness.

a)   b)

Figure 4. FSW process: a) schematic overview; b) geometric characteristics of the tool.

In this paper, the construction of the 3D finite element model of FSW process simulation is presented using the comercial FE software Abaqus. The pin is modelled as a rigid part, and has a reference point assigned, while the pieces are modelled as deformable parts. The rigid body surfaces are assumed isothermal.

The computational machine used for running the simulations has Intel based architecture with QUAD Core CPU running at 2.66GHz. The machine has a total installed RAM of 3 Gb. The operating system is Windows 8, 64 bits architecture.

4. Material model

The material used in this study is the Aluminium 6082-T6 alloy. AA 6082-T6 alloy generally present low weldability by traditional fusion welding process. In this work, material plasticity is governed by Johnson-Cook model [5]:

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

with: $\overline{\varepsilon}^{\,pl}$ - the efective plastic strain; $\dot{\overline{\varepsilon}}_{pl}$ - 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_{solid} is the material's solidification temperature.

Thermal and mechanical parameters of Al-6082 that were used in this analysis are shown in Table 2, were taken from references [6, 7].

Table 2. Constants for Johnson-Cook material model

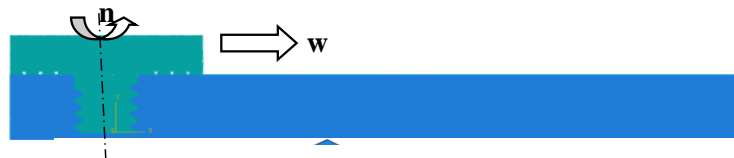| Material	$T_{melt}(^oC)$	A (MPa)	B (MPa)	C	n	m
Al 6082	588	285	94	0.002	0.41	1.34

5. Interaction, loads and boundary conditions

The contact between the elements is defined by Coulomb friction law with $\mu = 0{,}3$ [6], given by:

$$\tau = \mu \cdot \sigma_n \tag{2}$$

where: τ is the tangential stress; σ_n is the normal stress at the surface, and μ represents the coefficient of friction.

The contact between pin and deformable parts is a "general contact", in which tangential behaviour is described by a friction law and normal behaviour is described by a "hard contact", enabling the parties to separate after contact. This type of contact is associated with explicit dynamic analysis in the Coupled Eulerian-Lagrangian Formulation. The rotational speed and feed rate are $n = 1200$ rpm and $w = 180$ mm/min, respectively (Fig. 5).

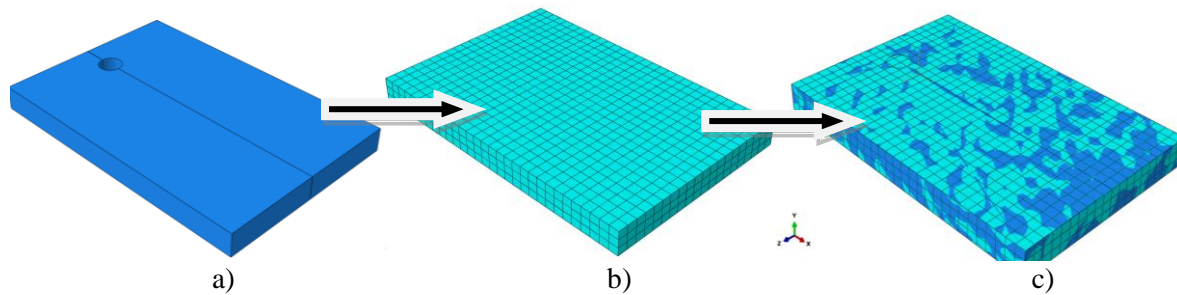
Figure 5. Boundary conditions.

6. Coupled Eulerian-Lagrangian formulation

Eulerian body is coupled to Lagrangian through contact interaction. Lagrangian reference frame is used to discredit the tool while Eulerian frame is used to discredit the workpieces. Simulations that include this type of contact are often referred to as coupled Eulerian-Lagrangian (CEL) analyses, Fig. 6. The Lagrangian mesh is attached to the material points. As the material deforms, the mesh deform with it. In contrast, the Eulerian mesh acts as a background grid. The mesh stays the same as the material deforms (or flows) inside the mesh. The extent of deformation in this case is measured when the material particle flows across an element node.

Eulerian analyses are effective for applications involving extreme deformation, up to and including fluid flow. In these applications, traditional Lagrangian elements become highly distorted and lose accuracy. During the welding process, the materials become viscous, and this state can be described efficiently by using an Eulerian analysis.

The Eulerian implementation in Abaqus/Explicit is based on the volume-of-fluid method. In this method, material is tracked as it flows through the mesh by computing its Eulerian volume fraction (EVF) within each element. By definition, if a material completely fills an element, its volume fraction is one; if no material is present in an element, its volume fraction is zero [9]. In this analyse we use a
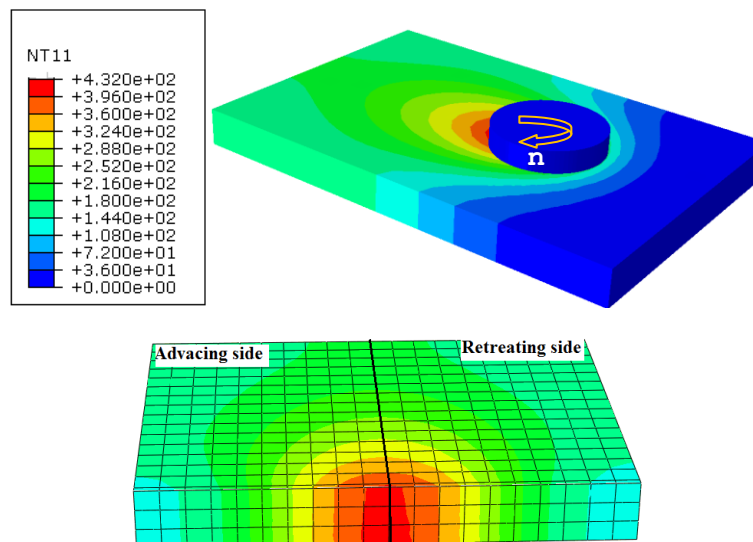
multi-material thermally coupled element type EC3D8RT. In the Coupled Eulerian-Lagrangian Formulation, the volume fraction tool uses the parts to be welded as a volume reference in the eulerian domain. The keypoint of this method is that the parts to be welded do not need to be meshed, only mesh on the Eulerian domain being necessary.

a)   b)   c)

Figure 6. Coupled Eulerian-Lagrangian formulation:
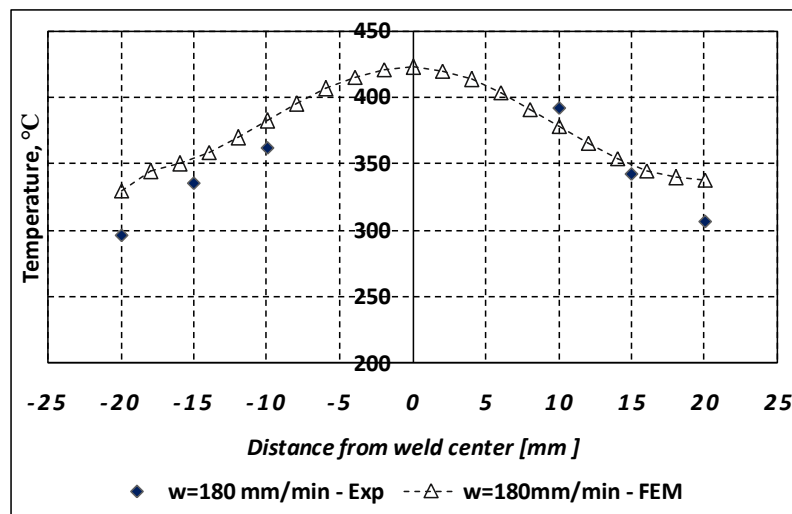a) Lagrangian body; b) Eulerian body; c) coupled Eulerian-Lagrangian

7. Results and discussions

The validation of the FE model was accomplished by comparing the temperature values obtained by the FE simulation with those measured experimentally. Fig. 7 show the temperature distributions predicted by FE model. The temperature distribution in the in cross section is not symmetrical with respect to the centre of the welding seam. The temperature is about 20°C higher on the advanced side than on the retreating side. Experimentally, the difference varies from 7 to 30°C, depending on the position of the thermocouple with respect to the welding seam.
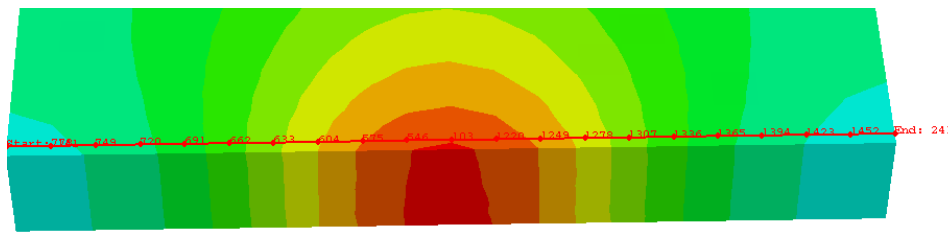

Figure 7. Thermal distributions predicted by FE model

The temperature values obtained experimentally and those obtained by simulation are plotted in Fig. 8.The temperature values were measured experimentally using the 6 thermocouples (see Fig. 2) and those obtained by simulation were taken from nodes placed on a line perpendicular to the weld seam (see Fig. 9).

Figure 8. Temperature distributions along cross-section in FSW joint

Figure 9. The spatial distribution of the nodes wich have been used to obtain the numerical values of the temperature.

We can see in Fig. 8 that the temperature values obtained by simulation were close to the experimental values. Consequently, we may consider that the model is validated. The maximum temperature difference is at a distance of 20 mm from the weld seam, in the advanced side, being about 30° C. This difference can be explained by the fact that, in the model, the boundary conditions were not imposed, in terms of heat exchange with the outside.

8. Conclusions

In this paper we focused on the numerical simulation of the FSW process, rather than the experimental characterization. FE model has been developed in Abaqus/Explicit software using the Coupled Eulerian-Lagrangian formulation, the Johnson-Cook material law and Coulombs law friction.

The main conclusions are summarized below:

- Coupled Eulerian-Lagrangian formulation allows modelling the large deformations that occur during the welding process;

- The model is validated using measured temperatures; the results of this FE model are in good agreement with the experimental results;

In the further research, the model presented in this paper will be enhanced by integrating a traverse feed in the FE model. Then, this FE model will be used to optimize the parameters of the FSW process.

Acknowledgements

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