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ACCURATE 3D FRICTION STIR WELDING SIMULATION TOOL BASED ON FRICTION MODEL CALIBRATION

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ABSTRACT: Friction Stir Welding (FSW) is one of the most effective solid states joining process and has numerous potential applications in many industries. A FSW numerical tool, based on Forge® F.E software, has been developed. Its main features are an Arbitrary Lagrangian Eulerian (ALE) formulation and an adaptive remeshing procedure based on error estimation. A 3D FSW simulation based on friction models calibration has been presented using Eulerian and ALE formulation. Two friction models have been studied to model friction in the tool-plate interface in aluminium alloy 6061-T6: Norton's and Coulomb's. Comparisons with experimental results considering various travel speed has been performed.

KEYWORDS: FSW, Friction calibration , ALE formulation, Al 6061, Forge3®

1 INTRODUCTION

This paper is focused on the calibration of friction models by 3D simulations of the FSW process. According to the very high tangential velocities and temperature rises, it is almost impossible to derive a simple experimental representative friction test for this process. Consequently the process itself is used for parameters calibration, by fitting numerical results with measured welding forces and temperatures in the welding tool. A 3D FSW simulation tool was developed by Guerdoux et al.[1], based on the Forge® F.E software. Its main features are an Arbitrary Lagrangian Eulerian formulation (ALE) and an adaptive remeshing procedure based on error estimation [2]. They have provided the expected accuracy at the tool/plate interface for simulating the three different process phases, plunging, dwelling and welding, with different kinds of tools, either convex or concave, either tilted or not, either threaded or not and have made it possible to carry out some preliminary friction calibrations [1]. The numerical simulations have initially been carried out using an Eulerian formulation assuming that the free surface of the material and more particularly the contact surface weakly depend on the values of friction coefficients. However, comparisons with plain ALE simulations showed that small modifications of these coefficients have significant influences on the material flow and consequently on the contact area, temperature field, contact stresses which drove us to use plain ALE simulations. Two friction models have been studied: Norton's and Coulomb's. Many simulations with various friction parameters have been successfully performed and compared to experimental results obtained from experiments conducted at the Brigham Young University.

2 FSW SIMULATION MODEL

A non linear elasto-viscoplastic model is used for the full coupling of the thermal calculations in the plate, welding tool and backing plate [1]. The Young modulus of the material is taken equal to 73 GPa and the Poisson's coefficient equal to 0.3.

The tool used for this study was manufactured from heat-treated H13 tool steel. Its dimensions consisted of a shoulder diameter of 25.4 mm, body length (from the top of the tool to the shoulder) of 83.8 mm and shoulder concavity angle of 8 degrees. The probe is 6.35 mm long and is unthreaded. The tool was used at a tilt angle of 2.5 degrees. The aluminium plate is made of Al 6061, with a thickness of 9.53 mm. As it is very large, in the finite element model its dimensions are reduced to a wideness of 150 mm and a length of 300 mm. It is assumed that the distance from the tool to the edges is large enough to allow proper computations of the thermal fields at steady state. The backing plate is also modelled, with the same dimensions as the workpiece and a thickness of 25 mm, as presented in Figure 1. In order to model the clamping system, two symmetry planes are applied on lateral sides of the workpiece.

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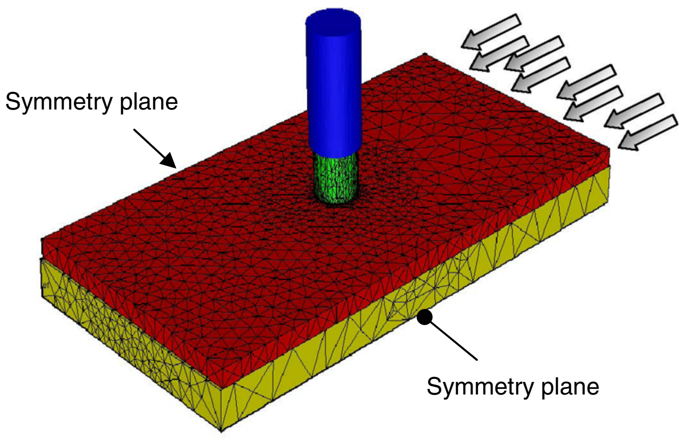

Figure 1: *Global view of the finite element model.*

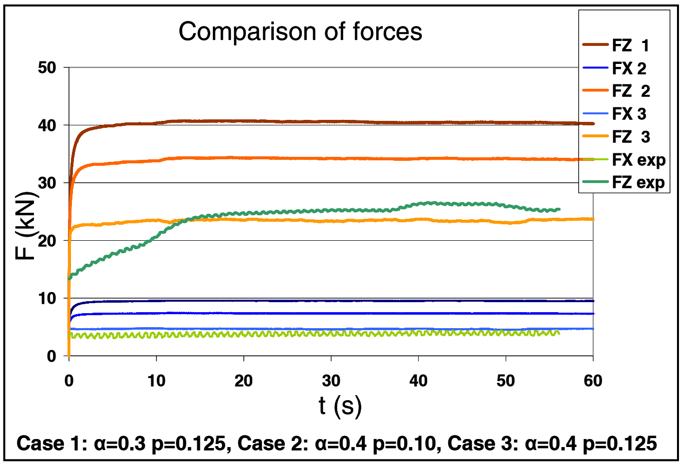

Figure 2: *Comparison of simulated forces for three different couples of friction parameters with experimental measures, versus time*

3 FRICTION CALIBRATION

In the following section, we present the two friction models used to simulate FSW process, either with an Eulerian formulation or with the ALE one, which is more accurate to actually compute the friction area and consequently the loads and temperatures in the friction area.

3.1 First approach of friction calibration based on an Eulerian formulation

In a first approach, the calibration is carried out with respect to the measured forces using an Eulerian formulation [1]. The Norton friction law required to identify two friction coefficients: α_f and the strain rate sensitivity q .

$$\tau_f = -\alpha_f K(T) \|\Delta v_s\|^{q-1} \Delta v_s \tag{1}$$

where τ_f is the shear stress, $K(T)$ is the temperature dependant material consistency and Δv_s is the relative sliding velocity defined by:
$\Delta v_s = (v - v^{Tool}) - [(v - v^{Tool}).n]n$.
Three welding simulations were carried out with different sets of coefficients. Case 1: α_f = 0.4 and q = 0.1. Case 2: α_f = 0.3 and q = 0.125. Case 3: α_f = 0.4 and q = 0.125.

Figure 2 shows that both vertical and horizontal forces are sensitive to small friction modifications and that a very good agreement is obtained between experimental measurements and simulation results for case 3.

However, the calculated temperatures in the FSW tool are not very consistent with the measurements. The maximum measured temperature is located at the tip of the pin, while the simulations provide the highest temperature at the shoulder sensor (see Figure 3).

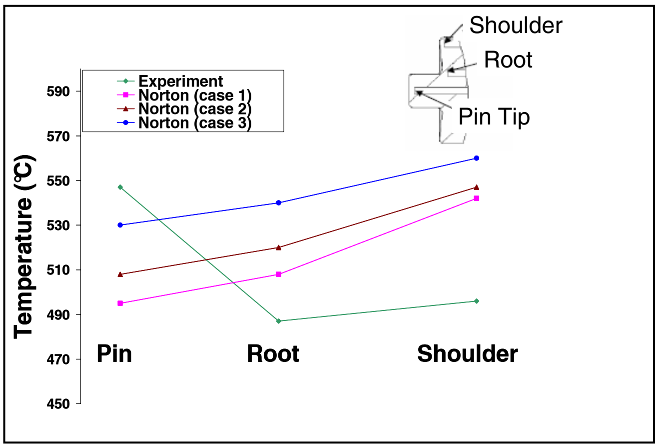

Figure 3: *Comparison of calculated and measured temperatures at pin, root, and shoulder locations in the FSW tool with a Norton friction, using an Eulerian formulation*

With the Norton model, a monotonic increase of temperature from pin to root and then to shoulder is observed for all cases, while in the experiments the highest temperature was measured at the pin followed by the shoulder and then the root. This first approach provides good agreement on forces but wrong tendencies on temperatures in the tool.

3.2 Second approach of friction calibration based on an Eulerian formulation

Based on experimental observations and on numerous works from literature [3-4], the Coulomb's friction law is now studied where the shear stress is proportional to the applied pressure (Equation (2)).

$$\tau_f = -\mu P \frac{\Delta v_s}{\|\Delta v_s\|} \qquad (2)$$

where μ is the friction coefficient, P is the contact pressure. Notice that in practice this law is limited by a Tresca's.

The calculated forces using Coulomb's model are listed in Table 2 and compared to measured forces.

Table 2: *Calculated and measured tool forces (with error bounds ΔF_{exp})*

	Fz(kN)	Fx(kN)
Experiments	24.8 ± 2.4	3.88 ± 0.7
Coulomb μ=0.2	30.2	7.97
Coulomb μ=0.25	25.4	6.36
Coulomb μ=0.3	21.8	5.06
Coulomb μ=0.4	17.4	3.77
Coulomb μ=0.5	14.3	3.01

The calculated forces provide good agreement with experiments taking into account the error bounds. Notice that this results confirm again that forces are sensitive to small friction coefficient modifications.

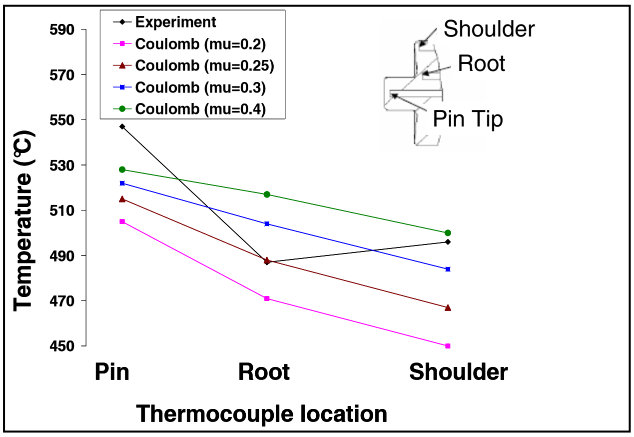

Figure 4: *Calculated and measured temperatures at pin, root and shoulder locations in the FSW tool with Coulomb friction using an Eulerian formulation*

Figure 4 shows calculated and measured temperatures, in the FSW tool with the different coefficients. In contrast with Norton model, the calculated temperatures present better trends. The maximum predicted temperature is located at the tip of the pin which is in agreement with experiments.

Figure 5 shows the Pareto diagram based on the relative error between measured and calculated forces and on the relative error on temperatures (horizontal axis) taking into account the error bounds (see Equations (3) and (4)).

$$\begin{cases} \text{if } |F - F_{\text{exp}}| < \Delta F_{\text{exp}} & \phi_F = 0 \\ \text{else} & \phi_F = \dfrac{|F - F_{\text{exp}}|}{F_{\text{exp}}} \end{cases} \qquad (3)$$

$$\phi_T = \frac{1}{3}\left[\frac{|T_{pin} - T_{pin\,\text{exp}}|}{T_{pin\,\text{exp}}} + \frac{|T_{root} - T_{root\,\text{exp}}|}{T_{root\,\text{exp}}} + \frac{|T_{shou} - T_{shou\,\text{exp}}|}{T_{shou\,\text{exp}}}\right] \qquad (4)$$

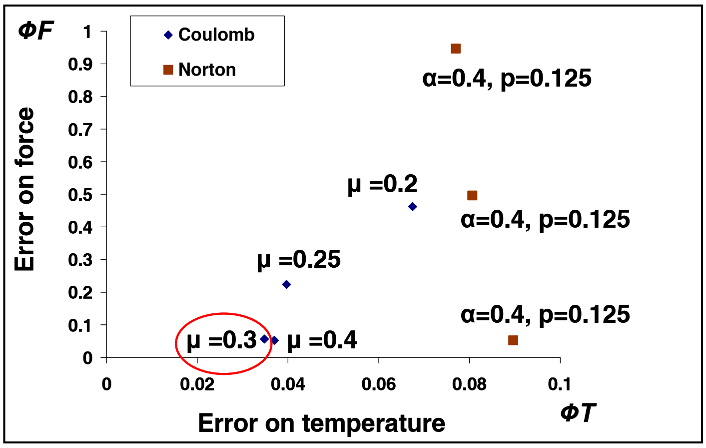

Figure 5: *Pareto plot, comparisons of Norton and Coulomb relative errors on forces and temperatures*

Figure 5 assesses the choice of Coulomb's law. μ=0.3 provides best results both on forces and temperatures.

4 ALE CALIBRATIONS AND VARIOUS TRAVEL SPEEDS

Plain ALE calculations show significant variations of the welding forces and tool temperatures due to a better prediction of the contact area: up to 8kN on forces with respect to previous Eulerian calculations and up to 30°C on the shoulder temperature.

4.1 ALE simulations

ALE calculations are then carried out with different Coulomb friction coefficients. The results are listed in Table 3.

Table3: *Comparisons of calculated and measured forces at steady welding states with the ALE formulation*

	Fz(kN)	Fx(kN)
Experiments	24.8 ± 2.4	3.88 ± 0.7
Coulomb μ=0.25	28 ± 2	4.2 ± 0.5
Coulomb μ=0.3	23 ± 2	3.8 ± 0.5
Coulomb μ=0.4	17.5 ± 2	2.8 ± 0.5
Coulomb μ=0.5	15 ± 2	2.1 ± 0.5

Calculated forces exhibits numerical oscillations caused by contact area changes under the shoulder and loses of contact behind the pin. The obtained results show that the best agreements on forces is obtained with μ=0.25 and μ=0.3. However, μ=0.25 provides is more satisfactory calibrations on temperatures (see Figure 6).

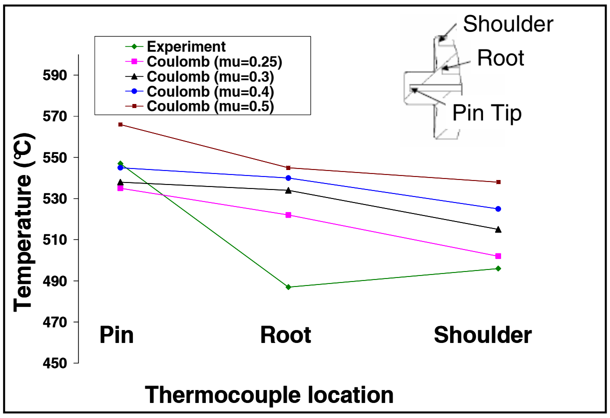

Figure 6: Comparisons of calculated and measured temperatures at pin, root, and shoulder locations in the FSW tool with Coulomb friction and the ALE formulation.

Comparing these results to those of Figure 5 shows that the tendencies of temperatures are the same but the values are different.

4.2 Various travel speeds

In order to validate the selected coefficients (μ=0.25 and μ=0.3), analyses have been carried out for large range of tool travel speeds. Table 4 summarizes the obtained results (forces and temperatures) for travel speeds of 4 inch per minute (ipm), 8ipm (the travel speed of the previous studies) and 12ipm.

Table3: Comparisons of measured and calculated forces and temperature obtained with the ALE formulation at various travel speeds.

	Fz (kN)	Fx (kN)	T Pin	T Root	T Sho
Exp 4ipm	19±2.5	3±0.2	545	485	495
μ =0.25	29	4.2	530	510	494
μ =0.3	21.5	3.2	535	524	510
Exp 8ipm	24.8±2.4	3.9±0.7	547	487	496
μ =0.25	28	4.2	535	522	502
μ =0.3	23	3.8	538	528	515
Exp12ipm	27±2	4.2±0.2	541	483	495
μ =0.25	29	4	528	512	494
μ=0.3	23.5	3.2	537	525	515

We observe the same quality of results as the one obtained previously with 8ipm, with a good agreement on forces and temperatures for all speeds.

Figure 7 shows the Pareto diagram obtained considering various travel speeds. Calculated results with different friction coefficients are compared to experiments. The relative error on forces (vertical axis) according the relative error on temperatures (horizontal axis) is presented in Figure 7.

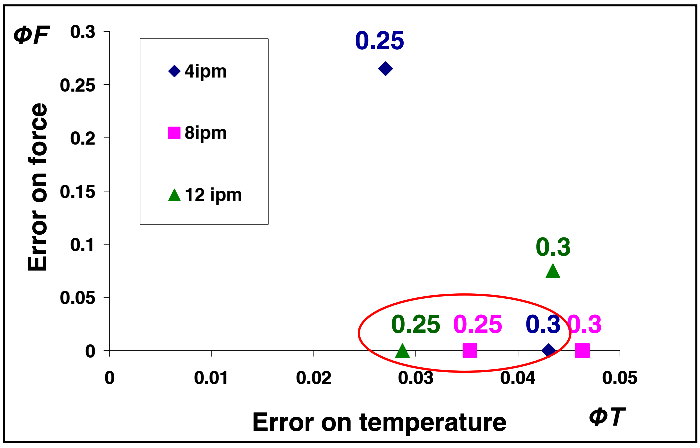

Figure 7: Pareto plot, error on forces according error on temperatures with the ALE calculation at various travel speeds.

5 CONCLUSIONS

A 3D FSW calibrations based on ALE and Eulerian formulations has been presented using Coulomb's and Norton's laws. It was shown that although the tendencies are the same with both formulations, the ALE provides significantly more accurate results. Calibrations on forces only is not determinant enough because and the Coulomb law provides satisfactory results and tendencies of temperatures. The study at various travel speeds provides the same quality of results which shows that this friction calibration can be regarded as rather general. However, the temperature in the tool is not perfectly modelled and certainly requires developing accurate model.

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