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3D numerical simulation of the three stages of Friction Stir Welding based on friction parameters calibration

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ABSTRACT: An Arbitrary Lagrangian Eulerian (ALE) formulation was developed to simulate the different stages of the Friction Stir Welding (FSW) process with the FORGE3[®] F.E. software. A splitting method was utilized: a) the material velocity/pressure and temperature fields are calculated, b) the mesh velocity is derived from the domain boundary evolution and an adaptive refinement criterion provided by error estimation, c) P1 and P0 variables are remapped. The proposed ALE formulation is applied to FSW simulation. Steady state welding, but also transient phases are simulated, showing good robustness and accuracy of the developed formulation. Friction parameters are identified for an Eulerian steady state simulation by comparison with experimental results. Simulations of the transient plunge and welding phases help to better understand the deposition process that occurs at the trailing edge of the probe, and in particular possible void formation. Flexibility and robustness of the model allows investigating the influence of threads and tooling designs.

Key words: Friction Stir Welding, ALE formulation, Friction, Adaptive remeshing, Remapping

1 INTRODUCTION

The Friction Stir Welding (FSW) process consists of a plunging phase that is followed by a stationary heating step, which prepares the actual welding phase. The simulation of possible defects (voids) formation during welding and of plunging requires accurately computing free surface movements while very large deformations take place under the tool. This issue is tackled by an Arbitrary Lagrangian Eulerian (ALE) formulation, which is used both for quasi Lagrangian plunging and quasi Eulerian welding. It is implemented into the Forge3[®] FE software [1], using a splitting method [2].

2 LAGRAGIAN STEP

The weak form of the momentum and incompressibility equations are written into a mixed velocity-pressure formulation that is discretized by a P1+/P1 quasi-linear interpolation based on 4-noded tetrahedron elements. Viscoplastic and elasto-

viscoplastic constitutive equations can be utilized to model material deformations with elastic spring back and residual stresses. Contact is handled by a penalty formulation, and friction conditions at the interface between part and tools are modeled by Coulomb or Norton friction laws. The discretized form of the heat equation is solved at each time step using an incremental coupling with the mechanical equations, both in FSW tool and backing plate. Heat generated by material deformation and by friction with the tool, thermal exchanges by conduction, convection and radiation, are thus taken into account to simulate all welding phenomena [1].

3 ALE SPLITTING FORMULATION

The ALE splitting method first consists in computing the mesh velocity \mathbf{w} , which can be different from the material one. \mathbf{w} is computed in order to optimize the elements quality and increase the computational accuracy, independently from the material deformation. It is based on error estimation (see [3] for more details) and must accurately

preserve the domain shape (see [4] for more details). The second step of the method consists in dealing with the convective terms that appear in time grid derivatives of any variable. Continuous nodal P1 fields are transported by an upwind technique [2], while discontinuous element wise P0 fields are transported in a Lagrangian manner using super convergent like techniques with equilibrated stresses (see [3] and [4] for more details).

4 STEADY WELDING STATE: FRICTION COEFFICIENT IDENTIFICATION

The size of the contact area between the tool and the workpiece results from many coupled phenomena: the friction area determines the intensity of the shear stress, which governs the intensity of the generated heat, which modifies the material viscosity and flow, which dictates the contact area ... So, this area has to be accurately calculated by taking into account all these phenomena. But it also requires a proper friction model, which requires a complex inverse analysis, which is approached here by calibration. The processing experiments have been conducted at the Brigham Young University by Sean Darby.

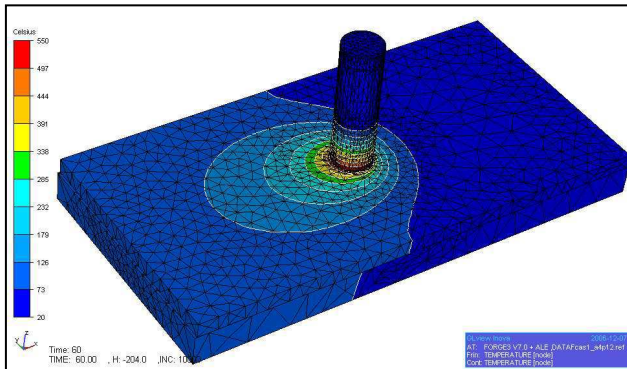


Figure 1. Temperature map at steady state (obtained after 60s of welding) for the calibration analysis

4.1 Friction model

During preliminary experiments, it was observed that the Norton friction model (1) provides more satisfactory temperature fields than the Coulomb one. It links the frictional shear stress τ_f to the sliding velocity Δv_s as follows:

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

In order to identify the α_f and q coefficients, three welding simulations were carried out with different

values. Case 1: $\alpha_f = 0.4$ and $q = 0.1$. Case 2: $\alpha_f = 0.3$ and $q = 0.125$. Case 3: $\alpha_f = 0.4$ and $q = 0.125$. The Eulerian formulation provides a robust and fast way to simulate the steady welding state corresponding to the experimental case (see Figure 1). The analysis of the simulated torques (see Figure 2) shows that this component is not sensitive enough to friction, and that the experimental data are too scattered (see Figure 2). On the other hand, the vertical and horizontal forces are very sensitive to small friction modifications (see Table 1), and so allow calibration: case 3 provides a very good agreement with experimental results (see Table 1).

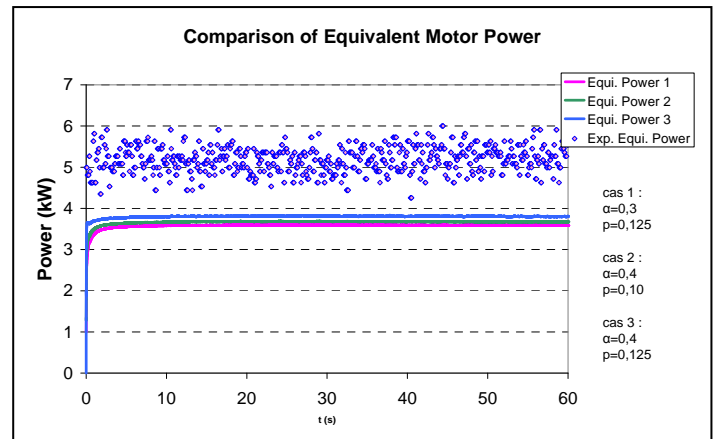


Figure 2. Comparison of simulated torques to experimental data, for the three couples of friction parameters.

Table 1 Calculated and experimentally measured tool forces at steady welding state

	Vertical force Fz (kN)	Traverse force Fx (kN)
Experiment	24	4
Simulated case 1	40.5	10
Simulated case 2	34.5	7.5
Simulated case 3	24	5

4.2 Transient Welding Phases & Defect simulation

The simulation of the transient states of the FSW process is made possible with the proposed adaptive ALE formulation. Figure 3 shows the temperature evolution during the successive steps of the process. An essential quality of the proposed model is its capacity to predict void formation, which is much trickier to do than with a damage model within an Eulerian frame. Figure 4 shows an example of a non-successful deposition where a void is formed at the lower advancing trailing side of the probe/matrix interface. Some voids form periodically while others turn into worm holes. Figure 4 shows that the void tends to be partially filled along with the process.

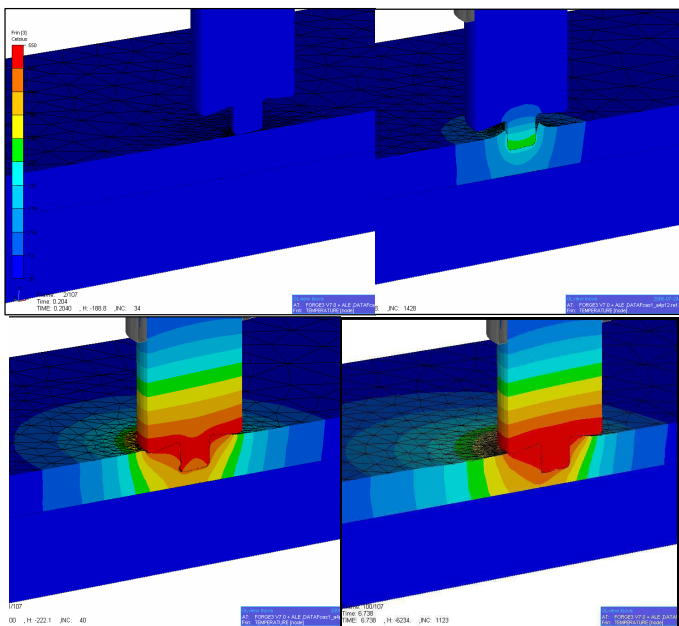


Figure 3. Temperature field (cross section view) at: initial state, plunging phase, after dwelling phase, transient welding phase.

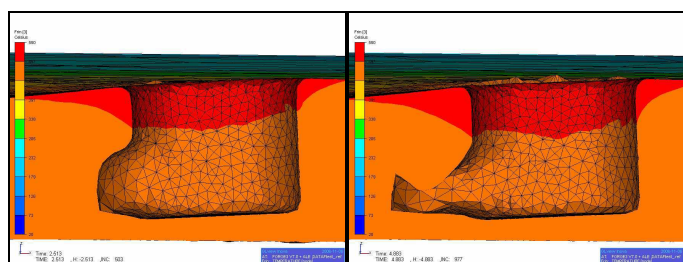


Figure 4. Void formation at back of the pin at $t=2.5$ s & $t=5$ s

4.3 Key points and encountered difficulties

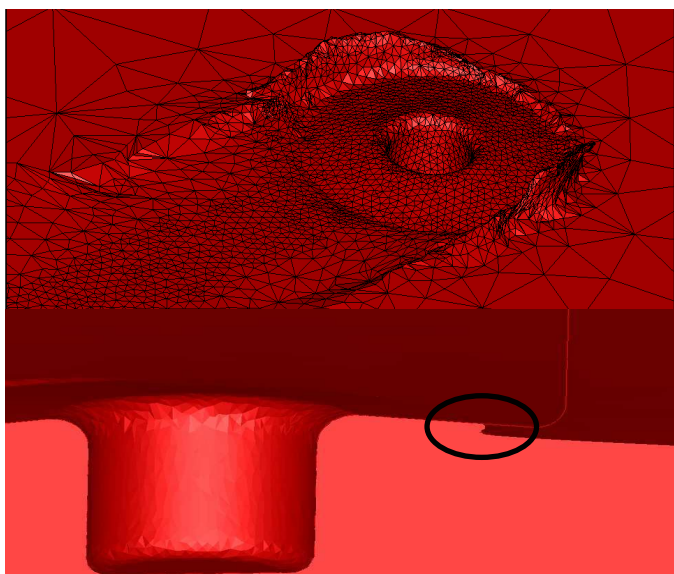


Figure 5. Simulation of flash formation (top) and of the occurrence of a fold at the end of the plunging phase simulation with a tilted tool (bottom)

On the one hand, the adaptive ALE formulation is expected to take into account any movements of the

free surface, like the significant amount of flash of the workpiece material that is generated during the plunging or welding experimental phases: the material curls up from beneath the tool when the tool penetration into the workpiece is deep enough (see Figure 5-top). Figure 5-bottom also shows the ability of the formulation to simulate very fine details (folds) of the process. However, these details are not significant for studying the process and their simulations might over pass the computational capacities. On the other hand, the plunge depth of the tool into the workpiece cannot be artificially modified because it is determinant in FSW. It actually influences the friction area and consequently the loads and temperature of the process. Therefore, the mesh regularization accuracy has to be adjusted accordingly.

4.4 Threads model

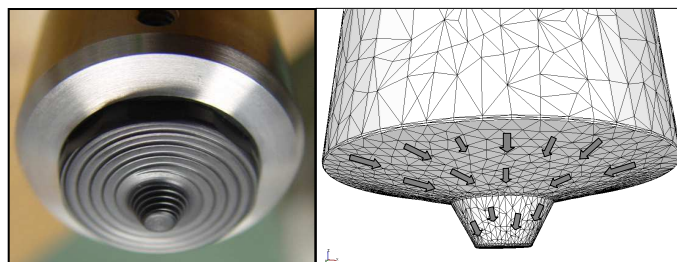


Figure 6. Convex tool (left) and virtual velocity (right) utilized to model the threads on conical shoulder and probe.

The influence of tool threads on material flow and heating is modeled by an additional virtual frictional velocity, which is applied perpendicularly to threads during the contact analysis, as presented in Figure 7.

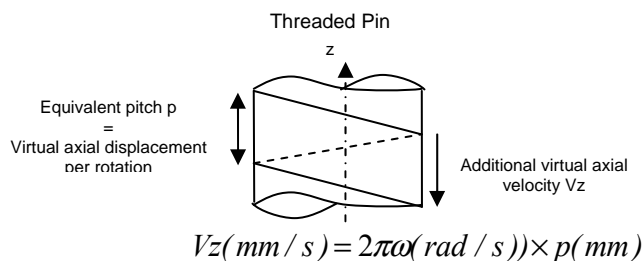


Figure 7. Illustration of the additional virtual axial velocity for modelling the influence of the threads.

Figure 8 shows that the threads result into a higher temperature with stronger gradients in the plate and tool. Looking into more details at the left bottom corner of the pin, or analyzing the contact distance, shows that there is a tendency of the material to leave the pin contact in the unthreaded situation.

This behavior disappears with the threads, which is the main reason of using them.

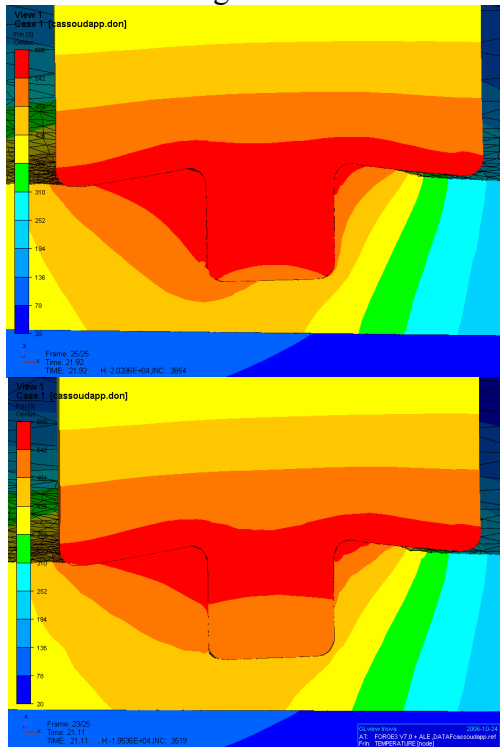


Figure 8. Temperature after 21 s of welding with threaded (top) and unthreaded (bottom) pin tool.

4.5 New tool geometry

The flexibility of the model allows studying different tooling designs, like the convex one presented in Figure 6. Figure 9 shows its foot print, and clearly demonstrates the role of threads, which is just the same as in Figure 8 with a concave tool.

5 CONCLUSIONS

The adaptive ALE formulation developed in the Forge3 software allows accurately simulating the three steps of FSW process, plunging, dwelling and welding, through a precise calculation of the actual friction area. The calibration of the friction coefficients of a viscoplastic law from experimental measured forces provides a remarkable agreement. Transient welding phases or phenomena such as void formation or threads influence can be simulated. The flexibility of the model also allows comparing different tool designs, which could be used for process optimization in the future.

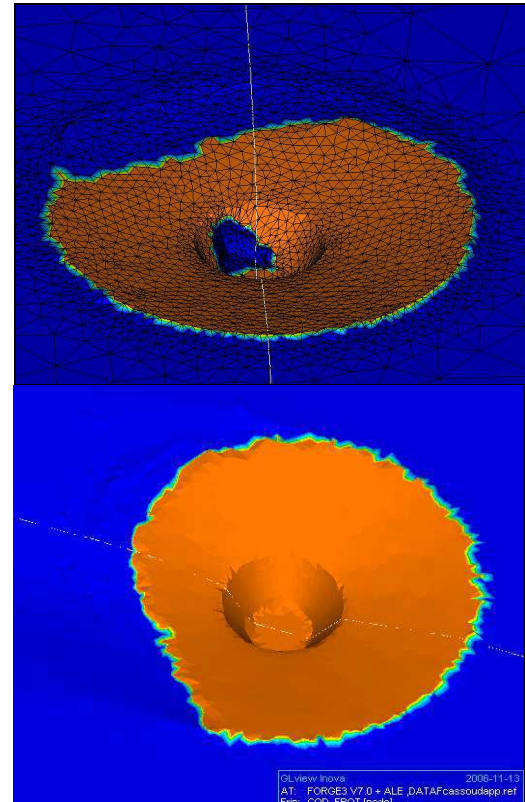


Figure 9. Contact area (in orange) of the convex tool after 17 s of welding without threads (bottom), with threads (top).

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