Universitat Politécnica de Catalunya

Master on Numerical Methods in Engineering

Numerical Simulation of Frictional Stir Welding Process

Industrial Training - Final Report

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Abstract

Friction Stir Welding process is a relatively new solid state joining technique, which offers a number of advantages over conventional joining process such as no gross melting of the welded material takes place. All these benefits render this process appropriate for different industrial applications where the metallurgical characteristics should be retained. This context has motivated the author to perform a numerical simulation of a Friction Stir Welding processes in a two-dimensional space with a circular pin, specific data and a prescribed geometry in order to analyze the behavior of the materials involved in this technique. The features chosen for Friction Stir Welding processes were as follows, the mechanical problem for the workpiece has been solved using a Bingham model. The pin is considered rigid. The model was discretized with triangular elements. The observed results for the temperature and the pressure were the expected one, due to the temperature increased along time while the pressure decreased. Additionally, the maximum value of temperature reached is lower than the melting point and no oscillations appears in the pressure. Finally, a sensitivity analysis was presented for the rotational velocity and the advancing speed.The obtained results present an expected behavior, that is, the value of the temperature increases for higher values of the velocities (rotational and advancing).

Keywords *Friction Stir Welding (FSW) process, advancing speed, rotational velocity, kinematic frameworks.*

1 Introduction

Friction Stir Welding (FSW) is a solid state joining technology in which the metal is not melted during the welding process. It is relatively a new technique, patented at The Welding Institute (TWI) in the UK in 1991. The basic concept of FSW can be described as follows: a shouldered pin is rotated at constant speed and plunged into the joint line between the two metal sheets butted together (Fig 1). Once the tool has been completely inserted, it is moved at constant advancing velocity along the welding line while rotating. During the process operations, a clamping system must keep the work-pieces rigidly fixed onto a backing bar to prevent the abutting joint faces from being forced apart. Due to the rotation and the advancing motion of the pin, the material close to the tool, in the so called stir-zone, is softened by the heat generated by the plastic dissipation(stirring effect) and the heat induced by the contact friction between the probe shoulders and the sheet. As a consequence, the material is stretched and forged around the rotating probe owing from the advancing side to the retreating side of the weld, where it can rapidly cool down and consolidate, to create a high quality solid-state weld.

This process offers a number of advantages over conventional joining processes such as welding fusion, absence of the need for expensive consumables, low distortion of the work piece and good mechanical properties of the resultant joint. Issues as porosity, solute redistribution, solidification cracking and liquefaction cracking do not arise during this process. In general, FSW has been found to produce a low concentration of defects and is very tolerant of variations in parameters and materials, for example aluminum alloys, nickel alloys and steel.

Nowadays, many companies are interested in the FSW process, as is the case of SAPA company, who requested to CIMNE to perform an analysis of the Friction Stir Welding process for a established data and for different shapes of the pin. For this reason, the aims of the present work are three principally. The first one is to know the basic concepts involved in the process of FSW. The second is to perform a 2D model analysis with a circular pin, in order to be familiarized with the interface, the results and the discretization of the mesh, and third one is to perform a sensitivity analysis for the rotating velocity and advancing speed.

The outline of the work is a follow: a description of the features of a fully-coupled problem model for FSW is presented. Additionally, the numerical simulation of a 2D FSW model is performed in the computational program COMET-FSW using parameters provided from SAPA GROUP company, which are the rotational velocity, the advancing velocity and the geometry. The evolution of temperature and pressure are analyzed in order to verify the correctness implementation of the model.

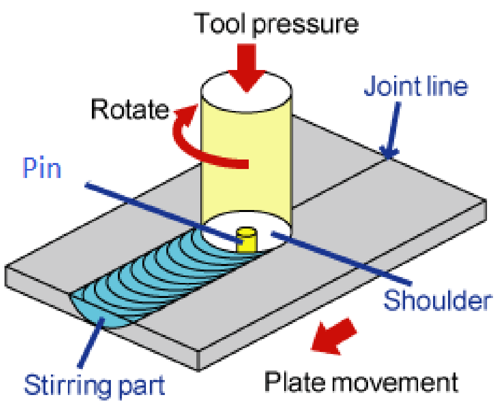


Figure 1: FSW process technology

2 PROBLEM STATEMENT

2.1 Kinematic framework

The choice of the kinematic framework is crucial for modeling FSW due to the computational efficiency and the solution quality. Therefore, the domain of the analysis is divided into three different zones which are the pin, the plate or sheet and the heat affected zone (HAZ), see figure 2, associating a specific kinematic framework to each one of them.

- Pin: the pin undergoes a rigid-body rotation at a constant speed and its deformation is not considered in the analysis. The kinematic framework associated is Lagrangian, which is a natural choice for the description of the pin's movement.
- HAZ: the heat affected zone is a part of the plate close to the pin where most of the material deformation takes place. The kinematic framework associated is ALE formulation because allows overcoming problems such as continuous re-meshing and re-definition of the domain for non-circular pin. In this work, HAZ is modeled as a circular region around the pin with the purpose that the outline does not change. The key idea consists in using the so-called mesh sliding, which in our case means rotating the HAZ mesh rigidly at each time step according to the pin movement, decoupling the material motion from the motion of the mesh.
- Sheet or Plate: The plate is the area lying outside the HAZ. The kinematic framework associated is Eulerian.

Coupling ALE and Eulerian parts at the interface requires a special treatment. The coupling is performed using a node-to-node link approach. Elsewhere, coupling the ALE and Lagrangian parts at the interface requires a special attention too. While the mesh velocity in both cases is equal, the material velocities, the pressure and the temperature are different. The contact between the pin and the HAZ material is generally characterized by nearly sticking condition. The case consider in the current work is full sticking, that is, the local material velocity matching that of the pin everywhere at the interface.

Details of the kinematic frameworks for the numerical modeling of FSW can be founded in [1].

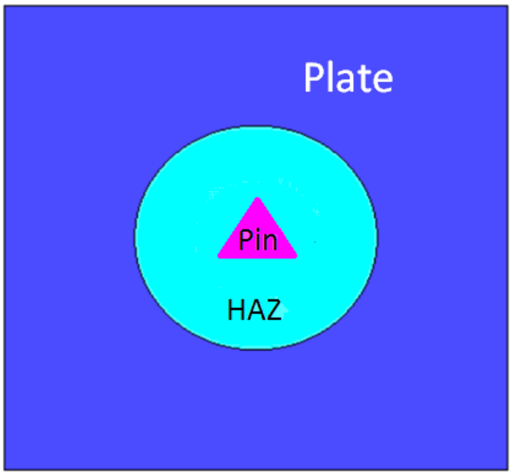


Figure 2: Kinematic zones

2.2 Governing equations

In this section, the coupled thermo-mechanical FSW model is presented. The governing equations are formulated within the kinematic framework explained previously.

Mechanical problem

The mechanical problem is defined by the momentum and mass conservation equations. Several assumptions are considered. First, the flow of the material around the pin is characterized by very low values of Reynolds number ($Re << 1$), due to very high viscosity of the material. Therefore, inertial effects can be neglected. Thus a quasi static analysis can be performed. In addition, the flow can be considered incompresible as the volumetric changes including thermal deformation are found to be negligible. Taking the above consideration and splitting the stress tensor into volumetric and deviatoric components, the mechanical problem can be written as:

$$\nabla \cdot s + \nabla p + \rho_0 b = 0 \quad (1)$$

$$\nabla \cdot v = 0 \quad (2)$$

where **s** is the deviatoric stress tensor, **b** is the body forces per unit of mass and **p** is the pressure. In FSW, the temperature gradient and the strain rate are very high in the vicinity of the pin requiring the use of rate-dependent constitutive models. In the present work, the material behavior is modeled as rigid visco-plastic. The model used is Bingham model. The Bingham model is a viscoplastic material that behaves as a rigid body at low stresses but flows as a viscous fluid at high stress, see figure 3.

Thermal problem

The thermal problem is governed by the energy balance equation, which in ALE framework is written as:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p v^* \cdot \nabla T = -\nabla \cdot q + \dot{D} \quad (3)$$

where v^* is the convective velocity arising from the difference between material velocity v and mesh velocity v . ρ, C_p, and T are density, specific heat and temperature, respectively. The last term $\dot{D}$ is the dissipation rate per unit of volume due to plastic deformation. The conductive heat flux q is defined according to the isotropic conduction Fourier law . The dissipation rate D depends on the

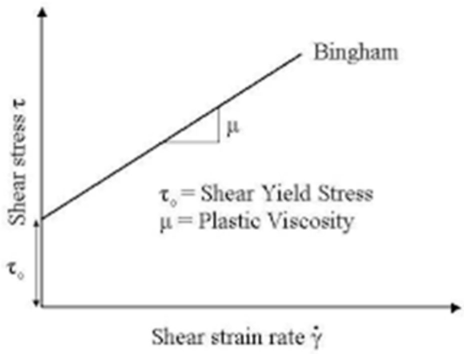


Figure 3: Bingham model

plastic strain rate and the deviatoric stresses. Therefore, thermal and mechanical models become coupled and the material parameters are temperature dependent.

Details of the governing equations, the local form of the FSW model, the weak form and the time integration can be founded in [2] .

3 Numerical simulation

A two-dimensional analysis is performed with the purpose to achieve the objectives established in the current work. It is important to indicated that even thought the pin presents a circular shape the three kinematic framework are used due to the interface of the program does not allow change it.

3.1 Geometry

The dimensions for the three zones are presented in figure 4. It can be observed that the pin presents a circular shape with a diameter equal to 4 mm. The HAZ presents a circular shape with a diameter equal to 14.5 mm and the sheet or plate domain presents a square shape with a edge equal to 29 mm.

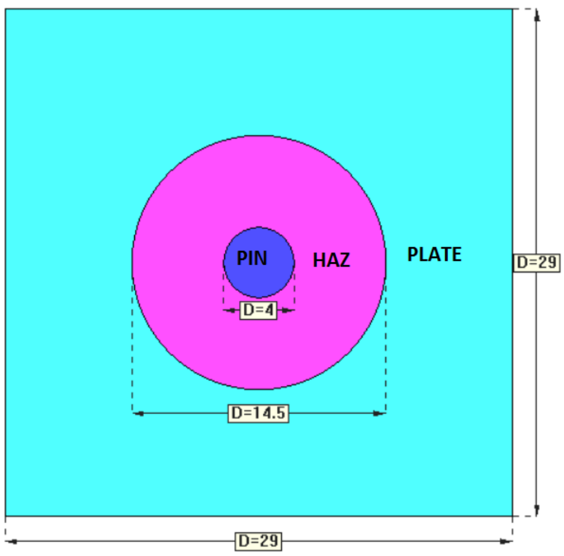


Figure 4: Kinematic zones (units in mm)

3.2 Material Parameters

- Pin: The material defined is steel. The mechanical properties are neglected. The thermal properties used in the simulation are the default ones for the steel given by the computational program, with a initial temperature equal to 20 Celsius degrees, see table 1.

Table 1: Thermal Properties (Pin)

Temperature	ρ (kg/m^3)	C_p (J/kg °C)	k (W/m °C)
1	7830	426.054	25.0
100	7799	485.524	26.0
200	7768	532.022	27.4
300	7737	565.122	27.3
400	7706	604.85	26.8
500	7675	665.538	26.4
600	7644	768.707	26.2
700	7628	1400.000	26.3
800	7611	890.604	26.8
900	7595	600.053	27.7
1000	7578	615.593	28.9
1100	7561	621.103	30.3
1200	7509	637.144	31.8
1375	7417	644.181	33.4
1430	7266	750.000	30.0
1458	7266	750.000	30.0
2000	7266	750.000	30.0

- HAZ and Plate: The Aluminum 6063 is defined as the material for both kinematics zones, because is the same work-piece in reality. The mechanical model chosen is Bingham, as it was indicated in the previous section. The initial temperature is equal to 20 Celsius degrees. The table 2 shows the values of the flow stress and the linear hardening, which are the parameters needed to define the Bingham model. It is important to note that these parameters are obtained using a given data with the mechanical behavior for different temperatures (maximum value 575°C) provided for the company SAPA. However, the temperature value equal to 660°C is approximately the melting point. For that reason an extrapolation procedure has been performed with the purpose to obtain the flow stress and the linear hardening(effective viscosity) for a range of temperature between 350°C and 650°C. The basic procedure can be described as follow: first an interpolation of the strain rate for every temperature is performed, the aim of this step is to obtain intermediate values. Second, the curves stress-temperature for every generated strain rate are extrapolated to get values until 650°C. Finally, a linear line-trend for every temperature curve for the range between 400 mm/mm.s and 2100 mm/mm.s is defined and the flow stress and the linear hardening are recovered.

  In addition, the thermal properties defined in the program have constant values, which are taken from [1], where the density is equal to 2700 kg/m^3, the specific heat is 896 J/Kg C and the thermal conductivity is 180 W/m C.

3.3 Boundary conditions

The values of the environment temperature, the number of revolutions, the convective heat transfer coefficient, and different values of the advancing speed and the rotational velocity are presented in

Table 2: Mechanical Properties (HAZ and Plate)

Temperature	Flow stress (Pa)	Linear Hardening (Pa)
350	$105.95 * 10^6$	5800
375	$98.575 * 10^6$	5700
400	$91.712 * 10^6$	5600
425	$85.325 * 10^6$	5500
450	$79.383 * 10^6$	5400
475	$73.853 * 10^6$	5300
500	$68.708 * 10^6$	5200
525	$63.921 * 10^6$	5100
550	$59.466 * 10^6$	4900
575	$55.321 * 10^6$	4800
600	$51.465 * 10^6$	4700
625	$47.877 * 10^6$	4500
650	$44.538 * 10^6$	4400
675	$41.432 * 10^6$	4200

table 3. These values are computed with the purpose to perform a sensitivity analysis of the velocities and check the correctness of the response of the model .

Table 3: Boundary Conditions

Case	V (m/s)	Ω (rpm)	T_{env} (°C)	N° rev	HTCCV (W/m^2K)
1	0.0050	400	20	100	25
2	0.0050	600	20	100	25
3	0.0440	800	20	100	25
4	0.0260	1600	20	100	25
5	0.0125	2900	20	100	25

3.4 Mesh discretization

The geometry of the model has been discretized using different finite element meshes. First a uniform mesh is used. However, the computational cost found is high and unnecessary due to the fact that the most important region is closer to the pin. For that reason, it is decided to use a mesh in the model, where the region closer to the pin presents a finer mesh. A convergence analysis for three non-uniform meshes is performed. The number of elements in the different zones are presented in table 4. The discretization of the three meshes is shown in figure 5. The element type is triangular.

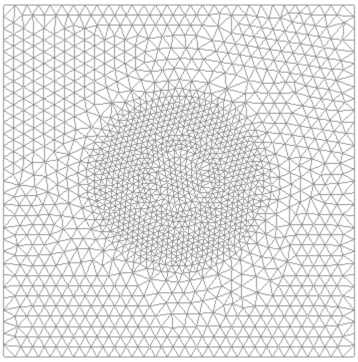
An studied of the evolution of temperature for an specific point (coordinates x= 0.0025 m and y=0 m)and case number five of the boundary condition (rotating velocity equal to 2900 rpm) is done in order to chose the most suitable mesh. It is important to note that due to for limitations in the computer memory a finer mesh in the HAZ is not possible. For that reason and together with the behavior observed in figure 6, which is that a finer mesh generates higher values of temperature then the mesh chosen is the third one, that is the sensitivity analysis and the check of the correctness behavior of the model is computed using mesh number 3.

3.5 Results and discussions

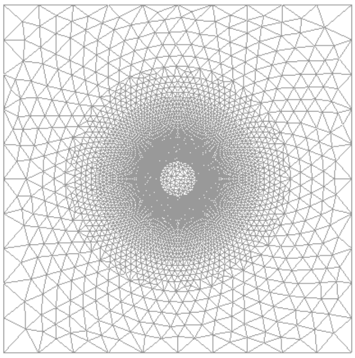
In this section the analysis of the temperature and pressure results are presented.

Table 4: Number of elements in the mesh

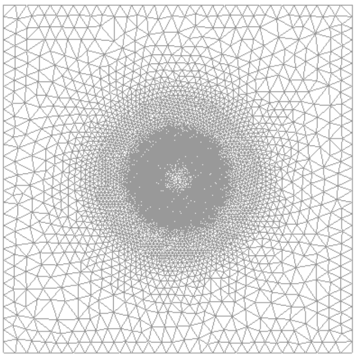
Mesh	PIN	HAZ	SHEET
1	1000	2532	1100
2	4354	14342	1608
3	32333	2669	2346



(a) Mesh 1



(b) Mesh 2



(c) Mesh 3

Figure 5: Mesh discretization

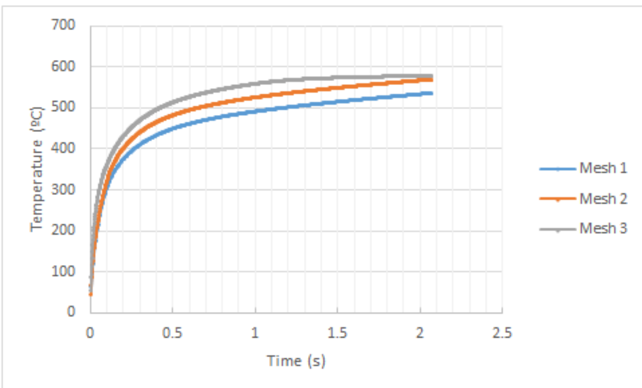


Figure 6: Evolution of temperature

- Temperature Analysis

  Figure 7 shows the temperature contour-fill. It can be observed that the zone close to the pin presents higher values of temperatures (red contour), which do not exceed the melting point ($T \approx 660$ Celsius), as is expected.

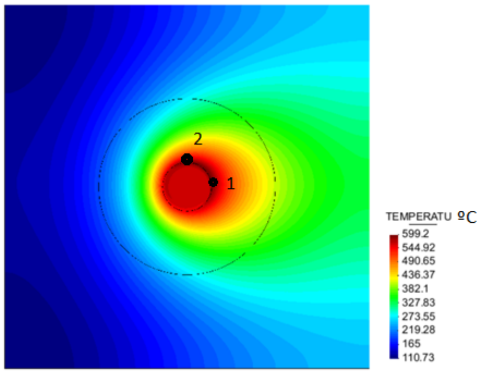


Figure 7: Temperature contour-fill

Fig 8 shows the evolution of the temperature for two spatial points. The coordinates for point 1 and 2 respect the center of the pin are (0.0025,0) m and (0, 0.004) m respectively. It can be seen that the temperature increase along time and on the other hand that point 1 reaches higher values of temperature than point 2, as is expected due to point 1 is closer to the pin.

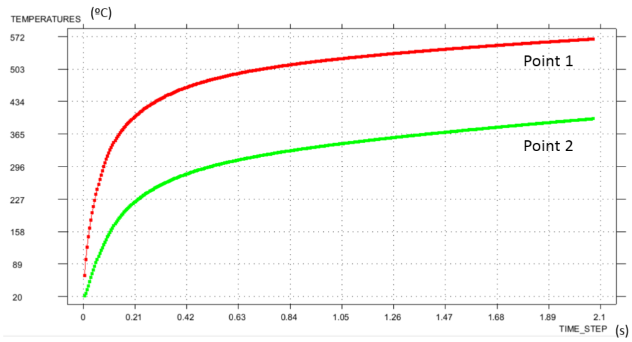


Figure 8: Evolution of the temperature in two spatial points

- Pressure Analysis

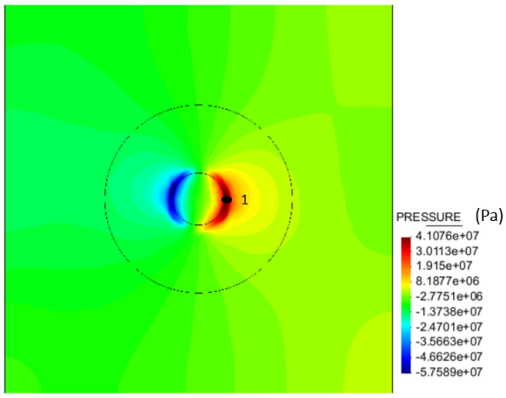


Figure 9: Pressure contour-fill

Figure 9 shows the pressure contour-fill. It can be observed that the behavior is approximately symmetric.

Figure 10 shows the evolution of the pressure for one spatial points, which coordinates are (0.0025,0) m. It can be observed that the pressure decreases along time, which is the expected behavior due to deformation on the material occurs. Additionally, no oscillations are presented.

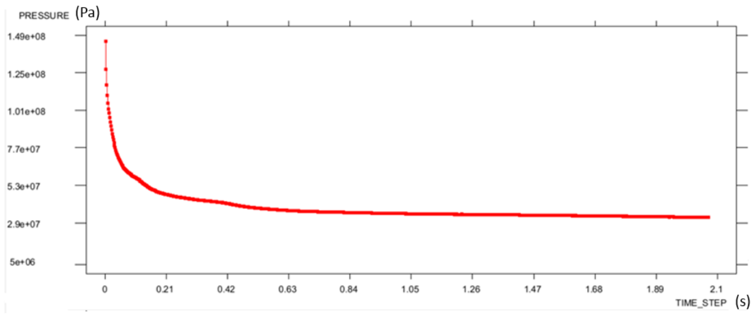


Figure 10: Evolution of the pressure in one spatial point

- Sensitivity analysis of the temperature

  Once the correctness implementation of the program is verified in the previous item, a sensitivity analysis of FSW process parameters is performed, specifically the rotating velocity and the advancing speed using table 3 for the five different cases presented in section Boundary conditions. Figures 12a and 12b show the evolution at two specific points, which are near to the pin interface. The coordinates of these points are presented in table 5. It can be seen as is expected that greater values of rotating velocity and advancing speed correspond with greater values of temperature. The behavior are not steady-state, however the trend show that with more revolutions will be reached. This study is because the computational cost for higher values of temperature is extremely expensive. Elsewhere, from figure 11 it can be said that for the same number of revolutions and ALE segments the total time of the model decreased for higher values of velocities.

Table 5: Coordinates of evaluated points

Point	x (m)	y (m)
1	0.0025	0
2	0	0.0025

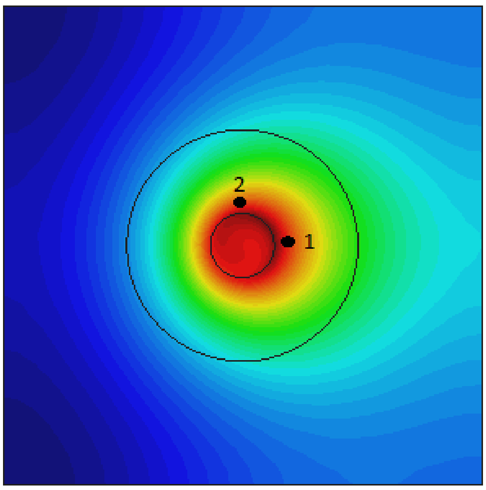
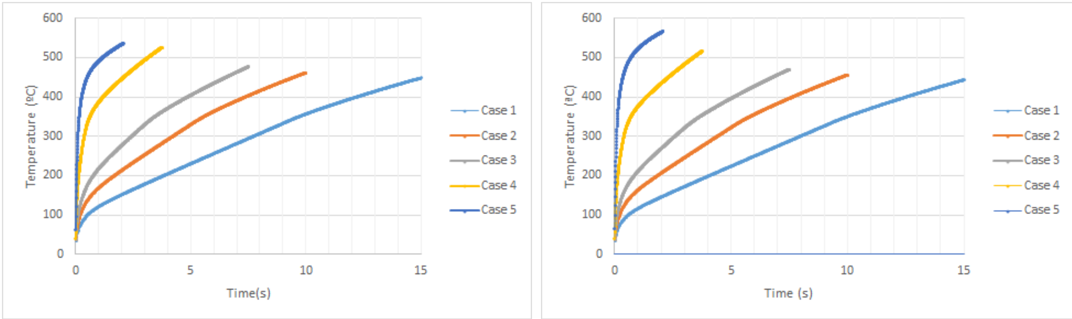


Figure 11: Coordinates of the points



(a) Point 1 (b) Point 2

Figure 12: Evolution of temperature

4 Conclusions

A thermo-mechanical 2D model had been implemented using a high value of the angular velocity (2900 rpm) in order to simulated the behavior of the friction stir welding process and check the correctness of the model for the most suitable mesh chosen after a convergence analysis. The maximum value of the temperature not reached the melting temperature, which is approximately 660 Celsius degrees and the location of this value is in the region near to the pin (stirring zone). The temperature increases in time while the pressure decreases. Finally, the sensitivity analysis shows that higher values in the velocities parameters generated higher values of temperature.

5 Future work

The future work aims to deal with a sensitivity analysis for different shapes of the pin. Finally, the numerical results must be compared against the experimental data with the purpose to validate the model.

References

[1] N. Dialami, M. Chiumenti, M. Cervera and C. Agelet de Saracibar,"*An apropos kinematic framework for the numerical modeling of friction stir welding*",Computers and Structures 117 48–57, (2013). 2012.

[2] M. Chiumenti, M. Cervera, C. Agelet de Saracibar and N. Dialami"*Numerical Modeling of Friction Stir Welding Processes*", Comput. Methods Appl. Mech. Engrg. 254 353-369 (2013).