Numerical Simulation of Frictional Stir Welding Process

María González-Gutiérrez
International Center for Numerical Methods in Engineering (CIMNE)
Universitat Politecnica de Catalunya
magonzalez@cimne.upc.edu

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 process were as follow, 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 value of the angular velocity is related with the discretization of the mesh. The observed results for the temperature and the pressure were the expected, 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.

Author Keywords

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

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 liquation 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 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 familiarized with the interface, the results and the discretization of the mesh, and third one is to analyze the impact of using high angular velocity values, which have not been studied in previous works.

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 analyze in order to verify the correctness implementation of the model.

PROBLEM STATEMENT

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

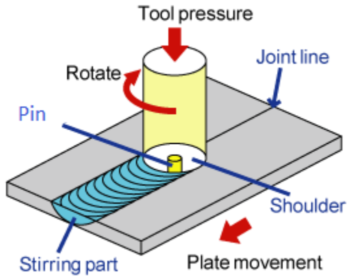

Figure 1. FSW process technology

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, as the flow there is predominantly rotational. 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 where the material flow is predominantly in the welding direction. The kinematic framework associated is Eulerian due to the domain do not change the shape and nor contains moving boundaries.

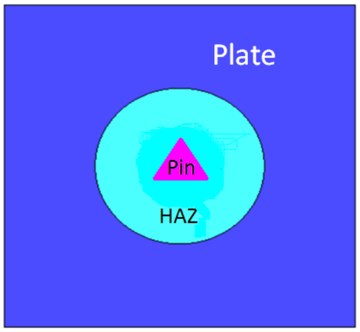

Figure 2. Kinematic zones

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

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 mecahnical 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 and convection can be neglected.Thus a quasi static analysis can be performed. In additon, 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, the mechanical problem can be written as:

$$\nabla \cdot s + \nabla p + \rho_0 b = 0 \tag{1}$$

$$\nabla \cdot v = 0 \tag{2}$$

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. Knowing that the Bingham modelis a viscoplastic material that behaves as a rigid body at low stresses but flows as a viscous fluid at high stress.

Thermal problem

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

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

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. 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 law Fourier. The dissipation rate D depends on the plastic strain rate and the desviatoric stresses. Therefore, thermal and mechanical models become coupled.

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

NUMERICAL SIMULATION

A 2D 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 the kinematic zones.

Geometry

The dimensions for the three zones are presented in figure 3. 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.

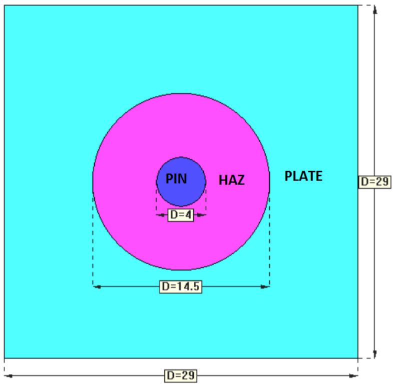

Figure 3. Kinematic zones (units in mm)

Material Parameters

- Pin: The material defined is steel. The mechanical properties are neglected due to no deformation is considered in the analysis. The thermal properties used in the simulation are the default ones given by the computational program, with a initial temperature equal to 20 Celsius.

- 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, how was indicated in the previous section. The initial temperature is equal to 20 Celsius. The table 1 shows the values of the flow stress and the linear hardening, which are the parameters needed to define the Bingham model.

Table 1. 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

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 specifi heat is 896 J/KgC and the thermal conductivity is $180W/mC$.

Boundary conditions

The advancing speed, the rotational velocity, the environment temperature, the number of revolutions and the convective heat transfer coefficient are presented in Table 2.

Table 2. Boundary Conditions

V (m/s)	Ω (rpm)	T_{env} (C)	N rev	HTCCV (W/m^2K)
0.0125	2900	20	100	25

Mesh discretization

The geometry of the model has been discretized according to different implementations. First a uniform mesh is used. However, the computational cost found is high and unnecessary due to the most important region is closest to the pin. For that reason, it was decided use an advancing mesh in the model, where the region closer to the pin presents a refined mesh (size of element approximately 0.01 mm) and the region far to the pin presents fewer number of elements (size of element equal to 1 mm), see figure 4. It is important to note that for the first approximation (uniform mesh) the size of the elements are greater than 0.5 mm and the results obtained are not accurate due to oscillations appears in the pressure. Using the same discretization of the mesh but imposing a angular velocity equal to 40 rpm the pressure obtained does not present oscillation.Therefore, the value of the angular velocity influences the discretization of the mesh because for higher values a refiner mesh is needed.

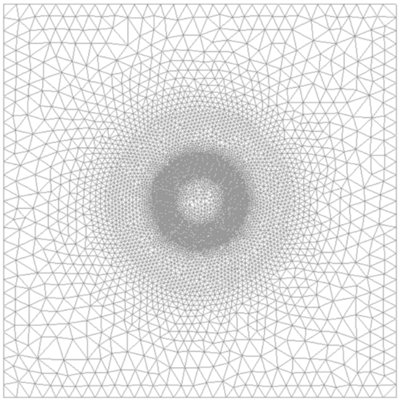

Figure 4. Discretization of the model

The element type is triangular because for industrial simulations must be used for the domain discretization. The number of elements for the plate is 2346, for the outer region of the HAZ is 4818, for the inner region of the HAZ (most important part) is 5860 and for the pin is 1024 elements.

Results and discussions

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

- Temperature Analysis

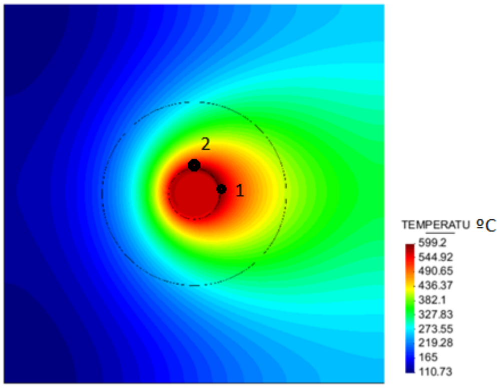

Figure 5. Temperature contour-fill

Figure N 5 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.

Fig 6 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 on hand hand, 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.

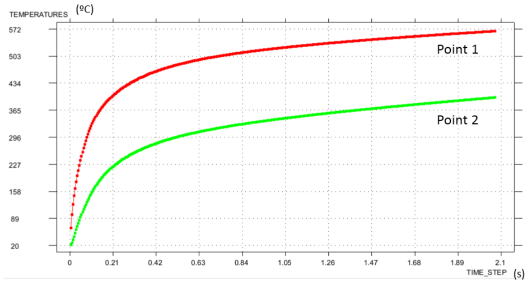

Figure 6. Evolution of the temperature in two spatial points

- Pressure Analysis

  Figure N 7 shows the pressure contour-fill. It can be observed that the behavior is approximately symmetric.

  Fig 8 shows the evolution of the pressure for one spatial points, which coordinates are (0.0025,0) m. It can be observed that the pressure decrease along time, which is the expected behavior due to deformation on the material occurs. Additionally, no oscillations are presented.

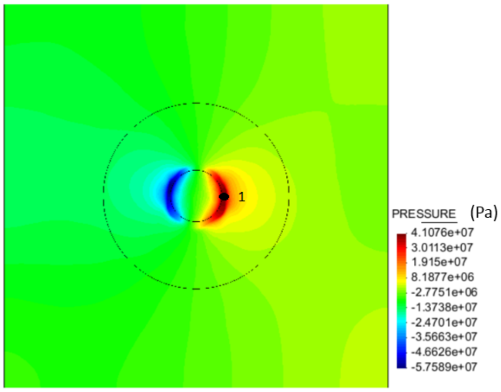

Figure 7. Pressure contour-fill

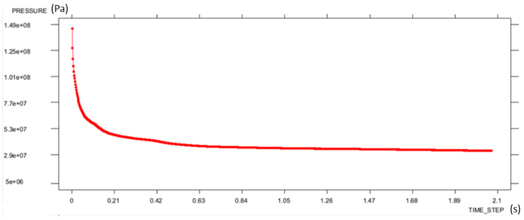

Figure 8. Evolution of the pressure in one spatial point

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. The maximum value of the temperature not reached the melting temperature, which is approximately 660 Celsius 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,a high value of the rotational velocity have a direct influence to the discretization of the mesh, in order to get stable and expected results.

FUTURE WORK

The current work is the first stage of the industrial training. The second stage involves a convergence analysis in order to choose the most suitable mesh to the model. In addition a sensitivity analysis of FSW process parameters should be perform in order to continue studying the influence of the rotation velocity in the model. Finally, the numerical results must be compare against the experimental data with the purpose to validate the model.

REFERENCES

1. N. Dialami, M. Chiumenti, M. Cervera and C. Agelet,"*An apropos kinematic framework for the numerical modeling of friction stir welding*", International Center for Numerical Methods in Engineering, Barcelona, Spain 2012.

2. M. Chiumenti, M. Cervera, C. Agelet and N. Dialami"*Numerical Modeling of Friction Stir Welding Processes*", International Center for Numerical Methods in Engineering, Barcelona, Spain.