A three-dimensional fully coupled thermo-mechanical model for Self-reacting Friction Stir Welding of Aluminium AA6061 sheets

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Abstract. In the present work a three dimensional model of self-reacting friction stir welding in aluminium alloy AA6061 has been developed based on the Computational Fluid Dynamics (CFD) approach using COMSOL Multiphysics software. The temperature dependent material properties have been incorporated in the model from available literature. A slip-stick contact between the workpiece and tool surface has been considered with the slip factor varying linearly with distance. The methodology adopted has been validated with experimental results available in the literature. The temperature distribution observed has been found to be asymmetric about the weld centre line. The maximum temperature has been observed on the advancing side of the weld. However, the temperature distribution across the thickness has been found to be almost symmetric about the mid thickness plane. An hourglass shaped temperature distribution has been observed across the cross-section of the weld. The material flow velocity distribution shows that the deformation zone is limited to a very small region around the tool.

1. Introduction

Friction Stir Welding (FSW) is a solid state welding process which was invented in 1991 at The Welding Institute, UK [1]. The present work is based on a variant of FSW known as Self-Reacting Friction Stir Welding (SRFSW) also known as Bobbin Tool Friction Stir Welding (BTFSW). The schematic of the process and the different stages are as shown in figure 1. The most important difference of this variant is the absence of the backing plate due to a modification in tool design which is inevitable in FSW. SRFSW is a full penetration welding technique and thus eliminates any chances of root defect which is quite common in FSW. It also promises to increase mobility of the process and bring about more homogeneity in the joints.

3D CFD models have been developed for studying BTFSW for AA2024-T3 assuming the material as a highly viscous shear thinning non-Newtonian fluid [2, 3]. In order to understand the material flow in BTFSW Chen et al. [4] carried out computer simulations and material tracer tests. Hilgert et al. [5] developed a moving geometry model in COMSOL and using some custom written scripts in MATLAB to account for the tool motion. The present work aims to develop a multiphysics FEM model of the SRFSW process for Aluminium alloy AA6061-T6 using its temperature dependent properties and study the temperature distribution in the workpiece and the bobbin tool. Also study the material flow in the vicinity of the tool based on computational fluid dynamics approach.
2. Methodology

An attempt has been made to develop a three dimensional fully coupled thermo-mechanical model based on computational fluid dynamics (CFD) approach for which a small region of the workpiece has been assumed to behave as a fluid. COMSOL Multiphysics software has been used in the present work. The temperature dependent properties of the workpiece and tool material have been incorporated into the model. The detailed description of the methodology has been presented in the following subsections.

2.1. Model description

The workpiece with a thickness of 4 mm and tool which has a simple cylindrical geometry with 8 mm diameter pin and 18 mm diameter shoulders have been used in the model. The workpiece and tool geometry is shown in figure 3. A small region along the weld line with a width of 30 mm has been considered to behave as a fluid and the remaining as solid. The fixture holding the workpiece in its position during welding has not been considered in this study.

Table 1. Composition of AA6061-T6 in weight percentage [6].

|          | Al    | Cu | Si  | Fe  | Mg  | Mn  | Cr  | Zn  | Ti  | Others |
|----------|-------|----|-----|-----|-----|-----|-----|-----|-----|--------|
| Weight % | 98.56 | 0.4| 0.8 | 1.2 | 0.15| 0.35| 0.15| 0.05| 0.05 | total 0.15 |
|          | 95.85 | 0.15| 0.7 | 0.8 | 0.15| 0.04| 0.25| 0.15| 0.05 | each (max), |

Table 1: Composition of AA6061-T6 in weight percentage [6].
2.2. Material properties

The workpiece is made of Aluminium alloy AA6061-T6 with composition as shown in table 1 [6]. The tool material is stainless steel. Temperature dependent properties of both workpiece and tool materials have been incorporated into the model. Figure 4 shows the variation of specific heat and thermal conductivity respectively of the two materials with respect to temperature [7][8][9].

![Figure 4. Variation of properties of aluminium with temperature: (a) Specific heat and (b) Conductivity [7][8][9]](image)

2.3. Boundary conditions

The contact between the tool and workpiece is not exactly known. Some researchers have assumed fully sticking condition but it eliminates heat input due to friction. In the present work the contact condition has been considered to be partially slip and stick and hence a slip factor ($\delta$) has been introduced as given by eq. 1, where $x$, $y$ are the coordinates from the origin at the centre of the tool and $R_s$ is the shoulder radius.

$$\delta = \frac{\sqrt{x^2 + y^2}}{R_s}$$  ...(1)

The coefficient of friction between two surfaces varies with the relative velocity and the actual coefficient of friction at each position is given by the relation in eq. 2 [10], where $\mu$ and $\mu_0 = 0.4$ are the actual and nominal coefficient of friction at various locations respectively, $\omega$ the angular velocity and $\lambda = 1$ s/m a constant to make the expression dimensionless.

$$\mu = \mu_0 \times e^{-\lambda \times \delta \times x \times y \times \sqrt{x^2 + y^2}}$$  ...(2)

The strain rate has not been considered constant at each position but has been calculated using the relation in eq. 3 [10], where $u$, $v$ and $w$ are the velocity components along $x$, $y$ and $z$ respectively.

$$\dot{\varepsilon} = \sqrt{\left(\frac{2}{3}\right) \times \left(\frac{d^2 u}{dx^2} + \frac{d^2 v}{dy^2} + \frac{d^2 w}{dz^2}\right) + 0.5 \times \left(\frac{d u}{dx} + \frac{d w}{dz}\right)^2 + 0.5 \times \left(\frac{d w}{dy} + z \frac{d^2 w}{dz^2}\right)^2 + 0.5 \times \left(\frac{d v}{dy} + \frac{d w}{dz}\right)^2}$$  ...(3)

The flow stress at the different locations is calculated using the eq. 4 where $Z$ is the Zener-Holloman parameter calculated using eq. 5 [11, 12]. $Q$ (134158.4 J mol$^{-1}$) is the activation energy, $R$ is the universal gas constant, T is the absolute temperature, $A$ (1.26×10$^8$ s$^{-1}$), $\alpha$ (0.03055 MPa$^{-1}$) and $n$ (3.24644) are material constants for AA6061 [12].

$$\sigma = \frac{1}{\alpha} \times \sinh^{-1} \left(\frac{Z}{\dot{\varepsilon}}\right)$$  ...(4)

$$Z = \dot{\varepsilon} \times e^{\left(\frac{Q}{RT}\right)}$$  ...(5)

The dynamic viscosity in the fluid region has been calculated using eq. 6 [11, 12].
The heat input due to the shoulder and the pin are calculated using eq. 7 and 8 respectively [11]. No external load has been applied and the pressure (P) developed in the process has been used to calculate the heat developed. A step function has been used in the relations to prevent heat input if the temperature in the workpiece at a location reaches solidus temperature (Tm). rp is the pin radius and T is the actual temperature at any location.

\[ q_s = \left( \frac{\sigma}{2\sqrt{\pi\delta}} + \delta \times \mu \times \rho \right) \times \sqrt{u^2 + v^2 + w^2} \times \text{step}(T_m - T) \quad \text{(7)} \]

\[ q_p = \left( \frac{\sigma}{2\sqrt{\pi\delta}} + \delta \times \mu \times \rho \times r_p \times \omega \times \sigma \right) \times \text{step}(T_m - T) \quad \text{(8)} \]

The ambient temperature has been assumed to be 300 K. The inlet surface of the workpiece as shown in figure 3 has been assumed to remain at the ambient temperature. Heat flow due to radiation has been neglected. However, heat dissipation due to convection has been considered from the upper and lower exposed surfaces. A physics controlled mesh has been developed using the software as shown in figure 5. The entire mesh contained 151922 elements with a minimum element quality of 0.01781 and an average element quality of 0.6945.

Figure 5. Mesh used in the study

Figure 6. Surface temperature (K) distribution

Figure 7. Temperature (K) profile in yz plane at x=0

Figure 8. Variation of temperature in the workpiece along the y-coordinate at x=0
3. Results and discussion
The surface temperature distribution obtained from the simulation is shown in figure 6. The temperature slice at x=0 shown in figure 7 establishes that due to heat input from two shoulders and the pin a saddle shaped temperature profile is formed in SRFSW unlike triangular profile formed in Conventional FSW. The temperature variation along the y direction (perpendicular to the welding direction) is shown in figure 9 and in the region closer to the tool is shown in figure 10. A higher temperature has been observed on the corresponding locations of the advancing side (AS) of the weld in comparison with the retreating side (RS). However, the variation in the temperature along the top and bottom surfaces of the workpiece is almost same. From the variation of temperature along the z-direction at 1 mm from the tool pin-workpiece interface as shown in figure 11 it has been observed that the temperature distribution is almost symmetric about the mid thickness which can be attributed to the uniform heat input from the two shoulders and the absence of backing plate unlike CFSW. The advancing side has been observed to be at a higher temperature. The flow can be visualized using the velocity streamline shown in figure 12. The velocity profile in the fluid region at x=0 is shown in figure 13. The profile is similar to experimental observations of a saddle shaped weld nugget zone. Between the tool shoulders some material has been observed rotating with the tool. Figure 14 shows the pressure distribution in the model.

Figure 9. Variation of temperature in the workpiece below the tool shoulder along the y-coordinate at x=0

Figure 10. Variation of temperature in the workpiece along z direction

Figure 11. Velocity streamline in the model showing the material flow. The velocity (m/s) slice at x=0 and velocity vectors are shown in the inset
4. Conclusions

Saddle shaped temperature and velocity profiles are observed which are similar to the weld nugget zone observed in experiments. The saddle shaped profile provides more homogeneity to the weld than the triangular shaped profile in CFSW which results in non-uniform mechanical properties across the thickness. A higher temperature has been observed at the corresponding locations of the advancing side which is similar to the observations in CFSW due higher frictional heat input as a result of higher relative velocity. The results indicate that some material keeps moving with the tool during welding due to the sticking condition. A slip-stick contact using a linearly varying slip factor has been used in the model and found to provide satisfactory results. The pin plays an important role in material mixing as indicated by the velocity profile and streamlines.

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