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Computational Fluid Dynamics based Transient Thermal Analysis of Friction Stir Welding

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Abstract
Friction Stir Welding (FSW) is a solid-state welding process that uses a rotating and translating tool to weld two materials together. The current study has been carried out in order to simulate the complex flow phenomena associated with FSW with much more realistic modelling. For this purpose, dynamic mesh has been used to simulate the translational motion of the tool, whereas sliding mesh technique has been employed to mimic the rotation of the tool. Temperature distribution within the materials being welded together has been critically analysed, and the predicted results have been verified against published experimental measurements of the same. The influence of the tool pin size on the temperature distribution has been investigated. It has been shown that the modelling technique adopted in the current study predicts the material flow and thermal distribution within the weld with reasonable accuracy.

Keywords: *Friction Stir Welding (FSW), Computational Fluid Dynamics (CFD), Thermo-mechanical Affected Zone (TAZ), Sliding Mesh, Dynamic Mesh*

I. INTRODUCTION

Since the invention of FSW, there have been many attempts to comprehend the physical phenomena that take place during this welding process. These phenomena can be affected by various welding variables, and determine the quality of the welded joint. Numerous studies have been carried out in order to understand the complex nature of FSW. Colegrove and Shercliff [1] employed a 3D steady state model to analyse FSW. It was observed that the size of the deformation zone predicted by the CFD solver was much larger than observed experimentally. As the definition of the fluid region in FSW in numerical analysis is a key issue for accurate modelling, Kang et al [2] modelled FSW by considering a rotational zone around the tool. Two different methodologies had been adopted in this study, the first being the one in which only the tool-workpiece contact area is forced to rotate, where the plastic zone grows in size as the heat dissipates. In the second method, the rotational region around the tool was defined as plastic deformation zone. A parametric study was carried out to determine the best shape of the affected region.

The transient numerical modelling of FSW, using Magnesium alloys, has been reported by Yu et al [3]. As the numerical model had been developed to investigate the material flow and heat transfer during FSW, the dynamic mesh concept had been utilised. Close agreement between the numerically predicted time-dependent temperature profiles and the experimental results of the same had been reported. However, defining the tool motion in terms of inlet flow velocity is still an approximation. Hence, the current study is an extension of Yu's work, where the translation motion of the tool has been specified using dynamic mesh technique, and considering the path followed by the tool as a solid region, rather than fluid. Moreover, the rotational region defined by Kang [2] has also been considered, while the rotation to the tool has been specified using sliding mesh technique. Hence, the numerical model considered in the present study is fully transient, where time-dependent temperature distribution within the solid region/s has been computed, and the predicted results verified against published literature that are based on experimental work, for aluminium alloy (AA2014-T6) for a tool with a triangular pin profile [4]. Moreover, detailed investigations on the effects of tool pin size have been carried out considering two more pin sizes of 3/2 and 1/2 of the original pin size.

II. NUMERICAL MODELLING

The numerical model of the computational domain is shown in figure 1. It consists of two plates of aluminium alloy AA2014-T6 in contact with each other. The tool, consisting of the shoulder and the pin, is being inserted into the workpiece at the interface of the two plates. The tool pin has a conical triangular profile with a length of 4.7mm, where the pin side lengths at the root and the tip of the pin are 5.19mm and 3.11mm respectively. The shoulder has a constant diameter of 12mm. The dimensions of the plates to be welded are 300mm x 100mm x 5mm. The numerical model has two main regions. The first region represents the thermo-mechanical affected zone (TMAZ) around the tool. This zone is treated as a fluid region which has a radial and conical shape, where its dimensions are based on design variables a and b, where the values of a and b are 1mm and 2.5mm respectively [2].

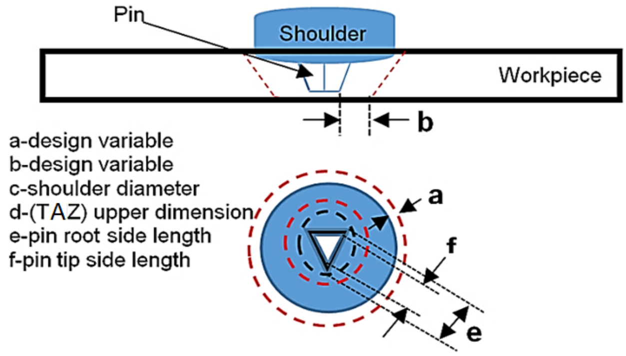

Fig.1 Numerical model of the computational domain

No-slip condition has been specified at the wall contact surface between the tool and the workpiece, and only conductive and convective heat transfers are considered. Furthermore, the heat generation due to tool's translation motion has been neglected. Due to the resultant heat generation from the rotational speed of the tool, the material behaves as non-Newtonian viscoplastic fluid in the near tool region, with laminar flow conditions. The fluid flow is governed by mass and momentum conservation equations, whereas, in order to specify the conductive and convective heat transfer rates, the energy conservation equation is also employed. These equations can be found in many published literatures such as by Arora [5]. By using the Finite Volume Method (FVM), these governing equations for 3D transient heat transfer and fluid flow are discretized and solved iteratively.

With a view to simulate the three main stages of FSW i.e. plunging, welding and retrieving, the tool has been specified with rotational and travel speeds of 1000rpm 7.73mm/s. To define the process heat generation, a heat flux was applied to the tool surface, which is being calculated using the analytical heat generation equation given as [6]:

$$Q = \frac{2}{3}\pi\mu\omega P(R_{Shoulder}^{3} + \frac{9}{4\pi}R_{prob}^{2}H_{prob}) \tag{1}$$

where, μ is the friction coefficient taken as 0.5 [7], ω is the rotational speed of the tool and P is the plunging pressure which is kept constant at 90MPa. As the heat generation is given by the above equation, it should be divided by the total surface area of the tool to give the heat flux. During the heat transfer analysis, the convective heat transfer coefficient specified at the top and side surfaces of the workpiece is taken to be 25W/m^2-°C. As the bottom surface of the workpiece is supported by a backing plate, the heat transfer coefficient value is considered to be 200W/m^2-°C [2, 8].

The chemical composition and temperature dependent properties, such as thermal conductivity and specific heat, of the aluminium alloy are provided in the literature [4]. A constant value of viscosity has been considered at the melting point [9]. The density of the material has been taken to be 2800kg/m^3 and it has been assumed to be constant as well [4].

III. RESULTS AND DISCUSSION

The CFD predicted time-dependent temperature profile has been recorded for 6 seconds of operation at a point having a transverse distance of 4mm from the weld centre, and at a depth of 2mm from the top surface of the plates. It can be seen in figure 2 that the CFD predicted temperature profile is in close agreement with the experimentally measured temperature profile at the same location. It is noticeable that the temperature increases exponentially with respect to time upto a certain point i.e. 4.5sec. The predicted temperature profile, however, depict a significant decrease in the temperature between 4.5sec and 6sec, as contrary to experimentally measured results, indicating a higher cooling rate. Furthermore, the static temperature distribution has been depicted in figure 3. It can be seen that the temperature is higher on the advancing side than on the retreating side, which is due to the opposite direction of the material flow on the advancing region to that of the tool motion.

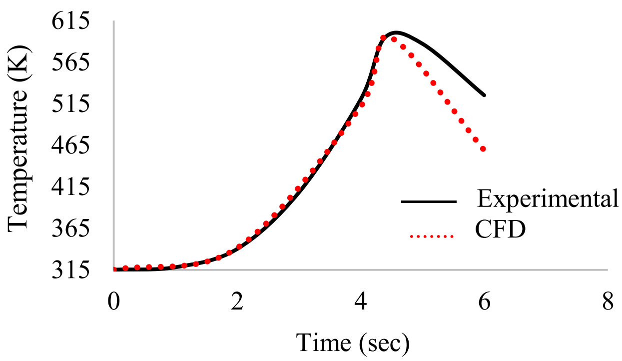

Fig.2 Comparison of the computed and CFD measured thermal cycles

Regarding the material flow behaviour, figure 4 represents the velocity vectors in the TMAZ region at the end of the operational time i.e. 6sec. As observed experimentally, the direction of advancing side material movement is downwards into the workpiece, while the movement of the retreating side material is upwards to the work piece surface. Some of the material may also be pushed out as flash, depending on the welding conditions [10].

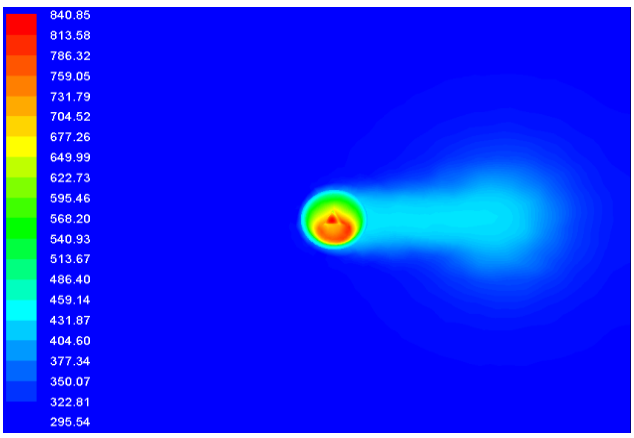

Fig.3 Temperature distribution within the flow domain at the end of the operational cycle

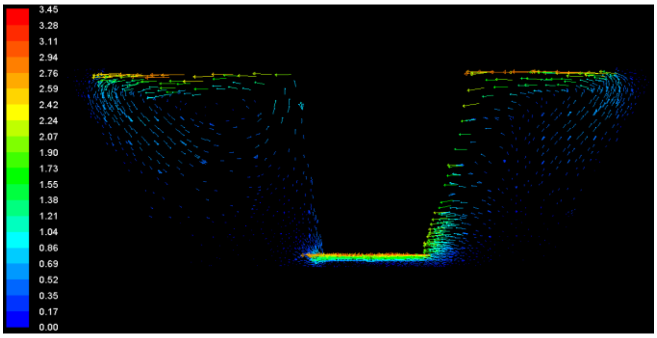

Fig.4 Velocity vector in the near-tool region at the end of the operational cycle

Figure 6 depicts the effects of the tool pin size on the temperature variations within the computational domain. It can be observed that as the tool pin size increases by 50%, the temperature valves throughout the cycle are negligibly higher as compared to the original size of the pin. Moreover, as the tool pin size decreases by 50%, the temperature values are, on average, 6% less as compared to the original pin size. Hence, it indicates that the origianl pin size considered in the present study is optimum as far as the temeprature distribution within a thermal cycle is concerned.

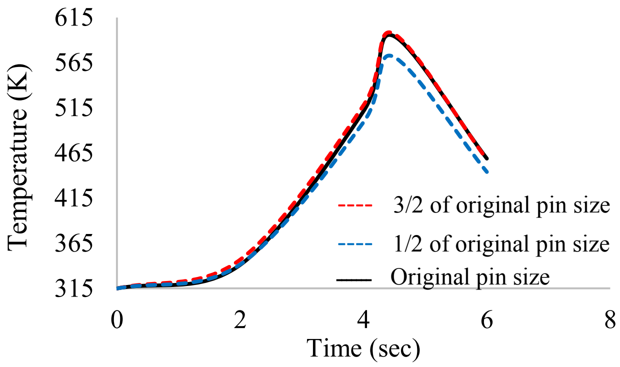

Fig.6 Comparison of the thermal cycles for different tool pin sizes

IV. CONCLUSIONS

Development and verification of a 3D time-dependent CFD based FSW model has been carried out for welding aluminium alloys together. The rotational motion of the tool has been specified using sliding mesh technique. Instead of specifying the translation motion of the tool as an inlet velocity of the fluid, dynamic mesh technique has been employed. Near-tool region has been modelled as a non-Newtonian viscoplastic fluid with laminar flow characteristics, and is representative of the TMAZ region. A comparison of numerically predicted and experimentally measured temperature profiles has been carried out, depicting similar trends for the same operational time. There are however some variations at the later stage of the cycle as CFD predicts significantly higher cooling rate. Furthermore, as the tool pin size increases, the heat generation remains unchanged, however, considering a smaller pin size significantly reduces the heat generation within the computation domain. Further investigations will be carried out in order to analyse the effects of a variety of tool pin sizes and shapes on the temperature distribution during the thermal cycle.

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