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Numerical Simulation of Friction Stir Welding Process to Investigate the Effect of a Conical Pin Tool with a Flat and Conical Shoulder on Heat Transfer

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Abstract

Friction stir welding (FSW) is a well emerged solid state joining process and requires continuous improvements. Since each tool geometry produces a different temperature distribution profile and moves the weld material differently, the current study considers a conical pin tool with a flat and conical shoulder to study its effect on heat transfer for a lap joint. For this, AA6061 material, along with its temperature-dependent properties, is considered. The geometric modeling is performed in Solidworks® 2017 and the numerical simulation in Computational Fluid Dynamics (CFD) software, Ansys® 19.2 R3 (FLUENT), utilizing the Finite Volume Method (FVM) approach. The result indicates that the high temperature contour lines at the conical shoulder surface are dispersed more towards the trailing side. At the transverse plane, temperature contour lines lean more towards the advancing side (AS). It is found that higher temperature is generated on the trailing AS, high temperature gradient on the leading side, maximum heat generation close to the tool shoulder region and the temperature decreases from top to bottom surface along the workpiece thickness.

Keywords

Friction stir welding, Finite volume method, Fluent

Introduction

FSW is a solid state joining process that was introduced by The Welding Institute [1]. It offers several advantages over conventional fusion joining methods, with no melting of the weld surfaces being the prominent one [2]. It is widely used for butt and lap welding of aluminum alloys, magnesium alloys, copper alloys, etc. FSW depends on factors such as geometry of the tool, tool tilt, rotational speed, welding speed, plunge depth, etc. These factors affect the heat transfer and material flow, which further determines the weld quality. One of the main factors determining the weld quality is the shoulder profile in tool geometry. CFD using FVM approach provides an efficient (cost-effective) and time saving tool for understanding them.

Investigation into this process has been carried out by many researchers with significant conclusions. Zhang et al. established a 3-D CFD model in fluent for studying temperature field and material flow behaviour using a conical tool, neglecting the tool tilt effect [3]. Tang and Shen evaluated preheating effect on temperature distribution and material flow using the FVM in FLUENT software on dissimilar butt FSW. A conical pin tool was employed with no tool tilt effect [4]. Kadian and Biswas studied the effect of tool pin profile on material flow characteristics using the 3-D transient CFD model in Ansys FLUENT, neglecting the tilt angle [5]. Zhao et al. established a 2-D transient CFD model to study the temperature distribution and material flow, neglecting the effect of

tool tilt and plunge depth [6]. Salloomi considered a 3-D numerical study, applying the Arbitrary Langrangian-Eulerian approach in Abaqus to a lap T-joint configuration to study the temperature, stresses, and strains [7]. A conical pin tool was used, neglecting the effect of tool tilt and plunge depth. Anand et al. investigated the input process parameters' impact on heat generation using a 3-D CFD model in FLUENT [8]. A conical pin tool with variable rotating speed and transverse speed was used, neglecting the effect of tool tilt and plunge depth. Wang et al. used Ansys for CFD-based simulation to study the stick-slip condition between the tool and workpiece and its effect on torque and heat generation rate [9]. They deployed a conical pin tool at variable rotating speed but constant transverse speed, neglecting the effect of tool tilt and plunge depth.

So, the effect of the conical pin tool with flat shoulder (CPFS) and conical shoulder (CPCS) needs to be understood as on the basis of literature review, tool geometry is an important parameter of FSW process to understand the heat transfer through temperature distribution. From the literature review, it is noticed that none of the researchers has studied this effect. Thus, the present work is an attempt in this direction, and we will try to assess this effect for aluminum alloy AA6061 in lap joint configuration. The geometric modeling is performed in Solidworks® 2017 and the numerical simulation is carried out utilizing the FVM approach in CFD software, Ansys® 19.2 R3 (FLUENT). The effect of tool flat and conical shoulder on heat flow is assessed by studying temperature distribution.

Numerical Simulation

Description of the model

Numerical modeling makes the visualization of the temperature field, material flow, stresses, and strains cost effective and effortless. It provides meaningful insight into the working of the process. FLUENT, a commercial CFD software, is used in this work to understand temperature flow behaviour.

The model utilized for simulation is given in figure 1. In the model, aluminum alloy AA6061 (with prior history of Direct Chill Cast (DCC) + Homogenization (H)) plates with the dimensions of 200 mm x 100 mm x 5 mm each are placed in lap configuration (i.e., 200 mm x 100 mm x 10 mm when combined together). The tool shoulder diameter is 25 mm, with a 2° conical angle. The length of the unthreaded pin is 5 mm, and the conical pin diameter is tapered from 8 mm to 6 mm. The tool rotational speed, weld speed and shoulder plunge depth are 60 rad/s, 0.001 m/s, and 0.5 mm, respectively. In physics, realizable k-epsilon viscous model is used for material flow in a steady state. To ensure good calculation accuracy, tetrahedron cells are considered in mesh (Figure 2). Fine mesh is considered at tool-workpiece interface and coarse mesh in the region away from the tool-workpiece interface as in this region, major heat transfer and material flow take place. The number of cells used for CPFS and CPCS is 729867 and 727278.

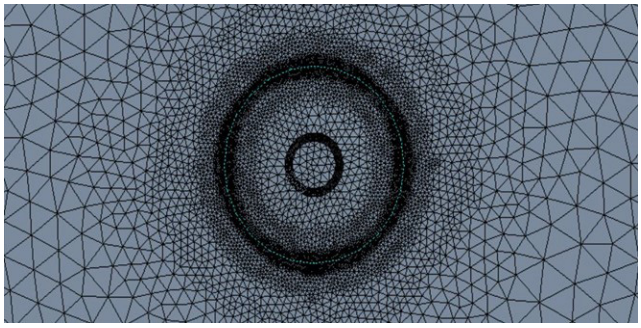

Figure 2: Mesh pattern used.

Three assumptions are made in the numerical model. To begin, heat is assumed to be generated at a constant rate (a quasi-steady process). The plasticized material is viewed as an incompressible non-Newtonian and visco-plastic material. Thirdly, the welding material is presumed to cling to the tool surface. The third assumption helps to study material flow behaviors qualitatively [3].

Boundary requirements and material characteristics

The model should represent boundary requirements close to the real physical environment experienced by the process as they play a significant role in the prediction of the true results. The model's parts and boundary requirements are presented in figure 3.

Flow boundary condition at inlet is defined as:

$$u = u_{weld}, v = 0, w = 0 \quad (1)$$

Where, respectively, u, v, and w are the magnitudes of the x, y, and z directions' velocities. u_{weld} is the welding speed. Free slip is defined for upper, lower, and side surfaces of the workpiece. Zero pressure value is assumed at pressure outlet for the

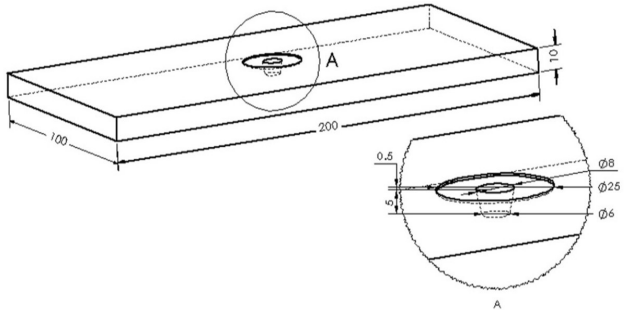

Figure 1: Computational model (All dimensions are in mm).

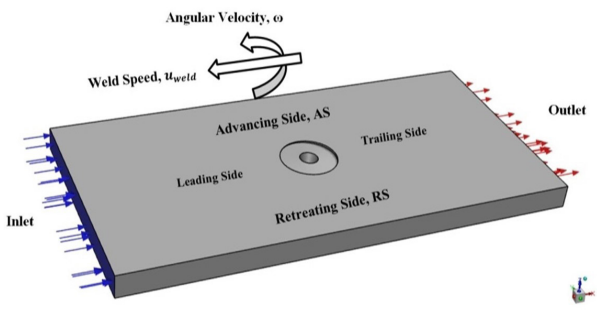

Figure 3: Boundary conditions of the model.

outlet boundary.

Tool periphery velocity is written as:

$$u_i = \omega r\sin\theta - u_{weld}, v_i = \omega r\cos\theta, w_i = 0 \quad (2)$$

Where, r value ranges such that $r_1 < r < r_3$. u_i, v_i and w_i represent velocity vectors in the x, y, and z direction, respectively; tool shoulder radius and pin bottom radius are r_1, and r_3, respectively; angle θ is equal to zero in the weld direction and is measured between the horizontal direction vector from the tool axis and any point on the cylindrical surface.

For fluid, η is non-Newtonian viscosity (dependent on temperature and strain rate), and is calculated from Equation (3) [10]:

$$\eta = \frac{\sigma}{3\dot{\varepsilon}} \quad (3)$$

Where, σ, T, and $\dot{\varepsilon}$ are flow stress, temperature, and strain rate, respectively. Both temperature and strain rate are read automatically via the FLUENT code. The viscosity equation is called using the User Defined Function.

The heat generated by various heat source surfaces is written as:

$$Q_{total} = (1-\delta)Q_{sticking} - Q_{sliding} \quad (4)$$

Where, δ is the variable for contact state. When δ = 0 (slip), the only source of heat is friction. When δ = 1 (stick), the deformation of plastic materials produces all heat [11]. Now, specific heat (C_p) and thermal conductivity (k) of AA6061 weld material [12] are represented by Equation (5) and Equation (6), respectively.

$$C_p = 929 - 0.627T + 1.481 \times 10^{-3}T^2 - 4.33 \times 10^{-8}T^3 \quad (5)$$

$$k = 25.22 + 0.3978T + 7.358 \times 10^{-6}T^2 - 2.518 \times 10^{-7}T^3 \quad (6)$$

The heat exchange boundary condition between the workpiece's top surface and the environment is convective heat transfer. Top, bottom, and side workpiece surface's heat dissipation coefficients are 30 W/m^{2}K, 500 W/m^{2}K, and 500 W/m^{2}K, respectively [12].

Results and Discussion

Model validation results

CFD model results need to be validated to predict confidence in the evaluated results. The present study started with a replication of the work reported by Zhang et al. [3]. The results for temperature distribution vary by 1.93%. The replicated results for temperature distribution are in close agreement with the results they reported. Thus, the methodology and procedure used for numerical simulation are validated successfully.

Effect on temperature distribution

The temperature distribution for the conical pin tool with the conical shoulder is shown in figure 4. Peak temperature generated is 759 K. Temperature generated on transverse plane of tool-workpiece interface is in the range of 457 K - 755 K. At the transverse plane, temperature contour lines lean towards the AS. The high temperature contour lines for CSS are spread more on the trailing side of the shoulder. The temperature contour lines are more dispersed at the trailing side than the leading side.

The temperature distribution for the conical pin tool with the flat shoulder is shown in figure 5. Peak temperature generated is 743 K. Temperature generated on transverse plane of tool-workpiece interface is in the range of 452 K - 743 K. The high temperature contour lines for CSS are spread on the trailing side of the shoulder. As the conical shoulder just increases the area for heat generation, the maximum temperature generated increases in comparison with flat shoulder. So, provision of conical shoulder does not affect the temperature distribution pattern when compared with flat shoulder.

General observations made during the study are written below. Generation of temperature is higher on the trailing side

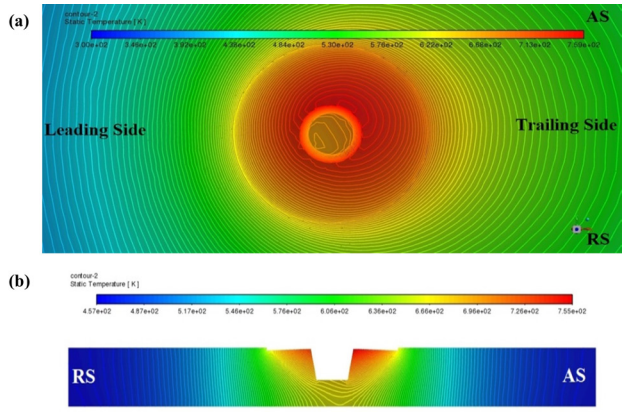

Figure 4: Temperature distribution for conical pin tool with conical shoulder. **(a)** Top view of tool-workpiece interface and **(b)** Transverse view of tool-workpiece interface.

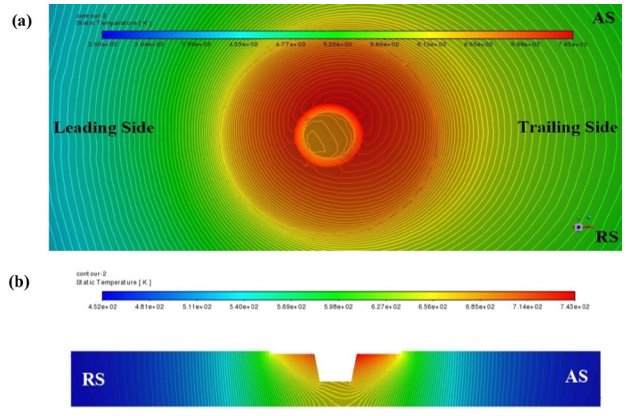

Figure 5: Temperature distribution for conical pin tool with flat shoulder. **(a)** Top view of tool-workpiece interface and **(b)** Transverse view of tool-workpiece interface.

of the AS due to high shearing rate and velocity which results in higher plastic strain and hence more heat generation.

High temperature gradient is developed on the leading side of the tool than the trailing side due to varied heat transfer capacities. The former is a cold region, and the latter is a preheated region. So, the transfer of heat takes place at a higher rate to the former region.

Since generation of heat is maximum along the region close to the tool shoulder and convection coefficient is maximum between workpiece-backing plate interface, the temperature decreases from top to bottom surface along the workpiece thickness. Since conical pin tool with conical shoulder produces higher peak temperature than conical pin tool with flat shoulder, the former tool is preferred.

Conclusions

The current study considers conical pin tool with a flat shoulder and a conical shoulder to study its effect on heat transfer. The high temperature contour lines at CSS are dispersed more on the trailing side. At transverse plane, temperature contour lines lean more towards the AS. It is found that higher temperature is generated on the trailing AS, high temperature gradient on leading side, maximum heat generation in region close to the tool shoulder and temperature decreases from top to bottom surface along the workpiece thickness. Since conical pin tool with the conical shoulder produces higher peak temperature than conical pin tool with the flat shoulder, the former tool is preferred.

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None.

Conflict of Interest

The authors declare no conflict of interests that are relevant to the content of this article.

Credit Author Statement

Amit Yadav: Conceptualization, Methodology, Resources, Investigation, Formal analysis, Writing - original draft preparation; Ajai Jain: Writing - review and editing, Supervision; Rajiv Verma: Writing - review and editing, Supervision. All the authors read and approved the manuscript.

References

1. Tsang S. 1993. Friction Welding. In Olson DL, Siewert TA, Liu S, Edwards GR (eds) Welding, Brazing, and Soldering, Volume 6. ASM International, pp 315-317.
2. Mishra RS, Ma ZY. 2005. Friction stir welding and processing. *Mater Sci Eng R Rep* 50(1-2): 1-78. https://doi.org/10.1016/j.mser.2005.07.001
3. Zhang J, Shen Y, Li B, Xu H, Yao X, et al. 2014. Numerical simulation and experimental investigation on friction stir welding of 6061-T6 aluminum alloy. *Mater Des* 60: 94-101. https://doi.org/10.1016/j.matdes.2014.03.043
4. Tang J, Shen Y. 2017. Effects of preheating treatment on temperature distribution and material flow of aluminum alloy and steel friction stir welds. *J Manuf Process* 29: 29-40. https://doi.org/10.1016/j.jmapro.2017.07.005
5. Kadian AK, Biswas P. 2017. Effect of tool pin profile on the material flow characteristics of AA6061. *J Manuf Process* 26: 382-392. https://doi.org/10.1016/j.jmapro.2017.03.005
6. Zhao PC, Shen YF, Huang GQ, Zheng QX. 2018. Numerical simulation of friction stir butt-welding of 6061 aluminum alloy. *Trans Nonferrous Met Soc China* 28(6): 1216-1225. https://doi.org/10.1016/S1003-6326(18)64759-4
7. Salloomi KN. 2019. Fully coupled thermomechanical simulation of friction stir welding of aluminum 6061-T6 alloy T-joint. *J Manuf Process* 45: 746-754. https://doi.org/10.1016/j.jmapro.2019.06.030
8. Anand RS, Prakash P, Jha SK, Singh AK. 2020. Numerical investigations of effect of input process parameters on heat generation in friction stir welding. *Mater Today Proc* 33: 5354-5361. https://doi.org/10.1016/j.matpr.2020.03.113
9. Wang X, Gao Y, Liu X, McDonnell M, Feng Z. 2021. Tool-workpiece stick-slip conditions and their effects on torque and heat generation rate in the friction stir welding. *Acta Mater* 213: 116969. https://doi.org/10.1016/j.actamat.2021.116969
10. Thomas WM, Johnson KI, Wiesner CS. 2003. Friction stir welding–recent developments in tool and process technologies. *Adv Eng Mater* 5(7): 485-490. https://doi.org/10.1002/adem.200300355
11. Hamilton C, Dymek S, Sommers A. 2008. A thermal model of friction stir welding in aluminum alloys. *Int J Mach Tools Manuf* 48(10): 1120-1130. https://doi.org/10.1016/j.ijmachtools.2008.02.001
12. Nandan R, Roy GG, Debroy T. 2006. Numerical simulation of three-dimensional heat transfer and plastic flow during friction stir welding. *Metall Mater Trans A* 37: 1247-1259. https://doi.org/10.1007/s11661-006-1076-9