Effect of tool geometry and process parameters on the material flow of friction stir welding.

Arun Kumar Kadian¹, Gautam Puri², Suman Das², Pankaj Biswas³*

¹Mechanical Engineering, IIT Guwahati, 781039, arun.kadian@iitg.ernet.in
²Mechanical Engineering, IIT Guwahati, 781039,g.puri@iitg.ernet.in
³Mechanical Engineering, IIT Guwahati,781039,pankaj.biswas@iitg.ernet.in

Abstract

The material flow behavior of friction stir welding is an emerging research area in past few years. In this present work two different tool geometries has been considered to study the material flow patterns of the welding process. A 3-D CFD analysis is performed with suitable boundary conditions to study the nature of material flow behavior of FSW process. A comparative study has been done based on the results obtained from numerical analysis for the two different tool geometries. The parameters used for the analysis of welding process also varied one by one for both the cases to achieve a good comparison on the effect of tool geometry on the material flow. The estimated material flow behavior compared well with those of the published results thus validating the various assumptions made in the work. It was observed that in FSW tool geometries has significant effect on material flow behavior.

Keywords: Finite Element Analysis, Transient Thermal Analysis, Combined Stick & Slip Condition, Friction Stir Welding.

1 Introduction

Friction Stir Welding (FSW) is a solid state welding method having a non-consumable tool without using filler material. The process was invented by The Welding Institute (TWI), Cambridge, UK and patented in 1991(W.H. Thomas). During this process the rotating tool moves material from advancing side to retreating side. So, it is important to know the manner in which the material behaves when it gets plasticized. The way in which the material flows in a friction stir welding process is need to understand to know the quality of the weld. The different parameter of the welds leads to different material flow behavior such as rotational speed, traverse speed etc. and a lot more depends upon the base material to be welded and its material properties at room temperature and when it reaches plastic state. The tool geometry is also considered the most important factor on which the material flow depends. The material flow directly influences the quality of weld or the kind of defect may arise after the welding. Since the material flow is not visible to naked eyes or any instrument in an experiment. It is very difficult to understand what is actually happening inside the welding process by experimental methods. So far, a very few attempts have been made to study the material flow behavior of Friction stir welding. E. Feulvarch et al. (2012)proposed a simple and robust moving mesh technique for finite element simulation of friction stir welding in which the heat transfer analysis and a material flow analysis can be achieved with a trigonal pin geometry. H. W. Zhang et al. (2007), (2004)H. Jamshidi Aval et al. (2011)investigated the material flow using temperature dependent material properties with the help of a finite element code using ABAQUS package. Some researchers like Lorrainet al. (2010), WU Chuan-song et al. (2012), Carter Hamilton et al. (2008), K. Kumaret al. (2008) made an attempt to understand the flow of material experimentally for an unthreaded cylindrical tapered tool and studied the microstructure of the weld zone. Rodrigues et al. (2014) worked on polymethyl methacrylate (PMMA) to investigate the material flow and thermo-mechanical analysis of friction stir welding.S.D. Jietal. (2012) used different threaded tool geometry to investigate the flow of material inside the base material in ANSYS Fluent package. They investigated the effect if tool shoulder on material flow. R. Kovacevic et al. (2003) introduced a moving coordinate in a transient 3D heat transfer analysis with the help of a mathematical model and analyzed a 3D model for different process parameter in commercial Finite Element package ANSYS considering sliding condition. Similar type of work was performed by G. buffa et al.(2011,12),D. Trimble et al. (2007) to predicted the residual stresses distribution with a 3D elasto plastic model Finite element model in DEFORM-3D™ and achieved a reduction in computational time.D. Jacquin et al. [17](2011) worked on a 3D thermo-mechanical model based on the model proposed by Heurtier et al. (2006) based on Eularian approach. Dongun Kim et al. (2010) utilized FVM code in STAR-CCM+ (based on eulerian formulation) to study the temperature histories at different welding parameters. So far not much work is done on material flow. It is an important area to work
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on so we have made an attempt to study the material flow behavior with four different tool geometries. It is a three dimensional numerical model which is implemented in ANSYS Fluent 14.0.

2 Finite volume models

The tool geometry consists of mainly two parts i.e. the tool shoulder and the tool pin. In this finite volume model the shoulder is taken as flat cylindrical while pin is varied. The two tool pin geometries taken for the analysis are the cylindrical and the conical shown in figure 1. The pin base diameter for cylindrical case is taken as 6mm, the shoulder diameter is as 25mm and the depth of pin is as 2.5 mm. For conical pin geometry the base diameter is taken as 6mm while the pin tip diameter is taken as 3mm. the shoulder diameter is also varied to understand the flow in a better way. The workpiece is also modelled and then meshed for further analysis. The dimensions of the workpiece are 150mm length, 50mm width and 3mm height. The two pin geometries are taken as cavities in the workpiece in the FVM model in ANSYS Fluent 14.0.

2.1 Boundary conditions

In the simulation of the welding process the tool movement is assumed to be form positive to negative x direction so the fluid flow was given in the opposite direction. The rotation of the tool is assumed to be in positive z direction e.g. anti-clockwise direction. To find out the effect of process parameters on material flow three different traverse speed of tool (1.8mm/s, 2mm/s and 2.2mm/s) and three different tool rotation speed (1000rpm, 1200rpm and 1400rpm) is considered. The temperature 1000K is given to pin wall. In this process the metal material is considered as a highly viscous non-Newtonian fluid. The contact between the rotational tool and material is considered to be no-slip contact. The material is considered to be in liquid state with temperature dependent viscosity. The input is given as moving wall with velocity 120mm/min and the other is considered as the output wall. The simulation is performed in FLUENTpackage. For simulation of FSW of the model, the RNG k-ω model is used. The RNG model is suitable for this case as it was developed using Re-Normalisation Group (RNG) in order to renormalize the Navier-Stokes equations so that effects of smaller scales of motion can be properly calculated.

![Figure 1: The model of the tool (a) cylindrical and (b) conical](image1)

2.2 Material properties

The workpiece material is Aluminium 6061 alloy, the composition of the alloy is given in table 1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Wt. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>95.8-98.6</td>
</tr>
<tr>
<td>Mg</td>
<td>0.8-1.2</td>
</tr>
<tr>
<td>Si</td>
<td>0.4-0.8</td>
</tr>
<tr>
<td>Cr</td>
<td>0.04-0.35</td>
</tr>
<tr>
<td>Mn</td>
<td>Max 0.15</td>
</tr>
<tr>
<td>Ti</td>
<td>Max 0.15</td>
</tr>
<tr>
<td>Cu</td>
<td>0.15-0.4</td>
</tr>
<tr>
<td>Other, each</td>
<td>Max 0.05</td>
</tr>
<tr>
<td>Zn</td>
<td>Max 0.25</td>
</tr>
<tr>
<td>Fe</td>
<td>Max 0.7</td>
</tr>
<tr>
<td>Other, total</td>
<td>Max 0.15</td>
</tr>
</tbody>
</table>

The density is 2700kg/m³ and it is assumed to be constant. The conductivity and specific heat is considered to be temperature dependent as the following table 2.
2.2 Governing equations

In FSW the material near the rotating pin gets plasticised due to frictional heat produced by the pin and tool shoulder. Considering the material a highly viscous fluid the finite element model can be made using commercial software. However to simplify the model simulation some assumption were considered

(a) There is no tilt angle given to the spindle of tool e.g. tool rotates perpendicularly inside the workpiece.
(b) The effect of tool shoulder is omitted.
(c) In contact between the surface of pin and workpiece is no slip condition.
(d) The molten material hasisotropic viscosity and is an incompressible fluid. The process of FSW follows the equations of mass conservation, momentum conservation and energy conservation. As the mass of material is constant so the mass conservation equation is given by:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

(3)

where u, v, w is the velocity in x, y, z direction respectively. The momentum conservation equation is given by the Navier-Stokes equation:

$$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = F_x - 1 \frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)$$

$$\frac{\partial v}{\partial x} + \frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = F_y - 1 \frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right)$$

$$\frac{\partial w}{\partial x} + \frac{\partial w}{\partial x} + \frac{\partial w}{\partial y} + \frac{\partial w}{\partial y} + \frac{\partial w}{\partial z} = F_z - 1 \frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right)$$

(4)

Where, \(F_x, F_y, F_z\) are the force in x, y, z direction respectively; p is the static pressure of the flow field; \(\mu\) is the viscosity of fluid and \(\rho\) is the density of material.

The energy conservation equation is given by:

$$\rho \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$$

(5)

Here, \(c\) is specific heat of material, \(\lambda\) is thermal conductivity of material, \(T\) is temperature of fluid.

3 Results and discussions

3.1 Effect of rotational speed

In order to analyze the influence of the any parameter on material flow various section of the weld plates observed. For better results three planes perpendicular to tool with normal parallel to the axis of the tool and one plane with normal perpendicular to the axis of the tool are considered. The surface 1 lies just below the tool shoulder (0.2mm below from top surface), surface 2 lies between the tool pin top and bottom (1.55mm from top surface), surface 3 lies just below the pin bottom (2.7mm from top surface). Surface 4 is parallel to the inlet surface and located at the mid-point of the rotating tool.

The tool traverse speed is taken constant as 2mm/s and the rotational speed is varied as 1000rpm, 1200rpm and 1400 rpm. For surface 3 the velocity vector is plotted coloured by velocity magnitude shown in figure 3. At all the surfaces it is noted that materials which are near to the rotating tool had very high speed and the direction of rotation is same as the tool i.e. anti-clockwise in the present case. It is observed that as the rpm of the pin is increased the speed of particles near the tool pin is also increased. High rotation velocity generates high deformation among the material near to weld region which ultimately leads to high strain rate values. Moreover, the region of deformation also increased with the
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increase in rpm value which is clear by the figure. At the pin bottom surface a swirl zone is present in which material flow had a rotating velocity. Particles that are closer to the outer side of the pin radius have higher value of rotation than that are just directly below the pin center.

![Figure 3: Material flow variation with rpm at surface 3.](image1)

3.2 Effect of translational velocity

For the effects of tool traverse speed on material flow the tool rotational speed is taken constant as 1200rpm and the rotational speed is varied as 1.8mm/s, 2mm/s and 2.2 mm/s. When material flow velocity vector by magnitude was plotted for surface 1, 2 and 3 it was found that for each surface the material flow pattern remains almost same for all the tool traverse speed. Material near the pin has same speed for all the cases as tool rotation speed is constant. As the tool speed increases the material flow near the pin rotates more for any surface. So the grain microstructure for higher tool speed will be more rotated then lower tool speed. Also the material flow width decreases as tool speed increases so less amount of material is stirred as shown in figure 4. At surface 1 the mixing of stirred material at the retreating side is found be good at 2mm/s speed but not at the other two speed of tool so to avoid a void optimum tool travel speed should be used.

3.3 Effect of tool pin geometry

The material flow varies with the tool geometry in respect of maximum velocity of the material around the pin and the stir zone. Velocity magnitude vectors at surface 1, 2 & 3 and velocity contour at surface 4 for the three different tool travel speed for both cylindrical and conical pin tool are observed and found that as the tool rotational speed remains constant, the maximum material flow velocity remained same for all the three tool travel speed in both type of pin tool. For cylindrical pin tool the maximum velocity is 0.286 m/s and for conical pin tool the maximum velocity is 0.305 m/s.No noticeable change in velocity contour in surface 4 for both the cases. This implies for a small change in tool travel speed the material flow remains almost same for both type of pin type.

![Figure 4: Material flow variation with tool speed at surface 3.](image2)

The material flow velocity contour is plotted on surface 4 of both the pin types as shown in figure 5. The tool travel speed for both the tool type is 2mm/s and the rotational speed is 1200 rpm. The highest material flow velocity is same for both the tool geometry. In both cases the highest material flow is obtained right below the shoulder surface of
tool. There is a significant dissimilarity between the velocity contours of these two i.e., the weld nugget produced will not be same for the two tool types. Also it is seen that the cylindrical pin gives better material mixing at the lower part of the weld, near pin wall. Chances of getting weld with lower penetration are higher in conical tool. This may lead to root defect.

Figure 5: The difference of material flow as the pin type changes from (a) cylindrical to (b) conical

From the velocity contours it is clear that maximum velocity attained by the material is same for both pin types. But that is only at the surface just below the tool shoulder. To study further the velocity vectors are plotted here for surface 2 is shown in figure 6. For conical pin, material just around the pin wall have velocity of 0.0156m/s while for cylindrical pin material just near the pin wall have velocity of 0.0776m/s, which is much higher.

The viscosity of the material changes with temperature it is lower when the temperature is high and higher when the temperature is low. So, the material away the tool rotation region is taken as highly viscous fluid i.e., effectively as solid but the viscosity near pin rotation region is considered to be low thus giving a better result. The variation of viscosity is shown in figure 7. Near the pin region and under the shoulder the viscosity is 0.01kg/m-s but just outside the tool the viscosity changes to 4kg/m-s and more as moves further away from the tool. The effect of variation of viscosity on temperature profile is shown in figure 8 and 9.

It can be seen from the picture that temperature produced in cylindrical pin tool is greater, as though heat generation by shoulder is same for both type of tools, the heat generation due to pin is greater for cylindrical tool. Also the temperature distribution is also differed especially in the retreating side because of the tool geometry difference.

3.4 Validation of model

For validating the model developed using FLUENT, it is necessary to correlate the developed model with the published results. For this purpose, the model is verified with experimental results obtained by V. Soundararajan et al. (2005).

The model used for validation has the same dimension that was used by them for experimental research. Two workpiece of Al 6061-T6 alloy with each dimension of 200x50x6.4 mm³ are butt welded. The tool shoulder radius is 12mm, pin radius is 3mm and pin height is 5.9mm.
The temperature was measured along a line whose distance from weld line is 6mm as in the experiment the thermocouple was also placed at 6mm distance from weld line. The tool travel speed is 133mm/min and tool rotation is 344 rpm.

The simulate results are plotted against the experimentally observed results which shows a good fit. So the FLUENT model is used for further analysis.

4 Conclusions

While simulating FSW it is important to consider heat produced by plastic deformation as it has significant contribution to the total heat generated at higher temperatures when deformation is significant. It is extremely important to consider the sticking condition in the analysis and thus the subsequent decrease in heat generation. The asymmetry in the temperature profile due to material flow can be estimated by assuming a simplified flow model and linking the heat absorbed to the time spent in the shear layer but an exact analysis requires a complete 3-D velocity field definition. Higher rotational speed leads to higher area of deformation and due to high rotational values near the tool surface, higher values of strain rates are observed. This is helpful from the thermal aspect of the process. This is probably caused by the increased friction heat generated. Thus from an isolated thermal stand point, increasing the rotational speed improves the heat generated and thus makes the weld better and thus a high value of maximum temperature is observed in case of high rotational values.

Increasing the transverse velocity of the tool reduces the temperature attained by the workpiece. This is probably because of the reduction in the deformation zone observed with higher values of traverse speed, though the velocity does not affect the power generated in the workpiece, it reduces the time the tool is present at a local position. Thus, reducing decreasing the heat generated at a particular spot.

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Thus from an isolated thermal standpoint it is better to perform the FSW process with low transverse velocities. The stirred material zone decrease slightly for increase in tool traverse speed at a constant rotating speed of tool. However for higher traverse speed the amount of rotation of plasticised material also increases so the grain structure will be similar to that obtained by slower traverse speed but more rotated. Also an optimum tool travel speed should be used to avoid bad quality weld at retreating side. The FLUENT model developed incorporates the
material flow phenomenon also and so it gives more accurate results. The effect of tool travel speed and tool rotation on material flow and temperature history is modelled. Increasing tool travel speed or decreasing tool rotational speed decreases maximum temperature attained by the weld. Tool speed has less effect in material flow than tool rotation. The effect of tool pin geometries of temperature contour and material flow is discussed. Taper pin tool gives less amount of material mixing than cylindrical tool and also decreases the maximum temperature attained by the weld.

References


