Prediction of Thermal History of Friction Stir Welding by Considering Combined Stick & Slip Condition of AA1100

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Abstract

In the present work three-dimensional Finite Element (FE) transient thermal analysis of friction stir welding have been presented. It was observed that most of the research on thermal history analysis of Friction Stir Welding (FSW) considered only frictional heat generation. In this present work the source of heat generation have been assumed to be both friction between the tool and work piece interface and shear deformation of material. A comparative study has been done between thermal history prediction by heat generation due to friction and heat generation due to both friction and shear deformation of material. The numerically predicted thermal profiles compared well with those of the experimental results with less error thus validating the various assumptions made in the work.

Keywords: Finite Element analysis, Transient Thermal analysis, Combined Stick & Slip condition, Friction Stir Welding.

1 Introduction

A Continuous research is going on FSW for improvement the process which came into picture in 1991. The process was invented by The Welding Institute (TWI), Cambridge, UK and patented (W. H. Thomas). Many numerical and simulation models have been proposed and modified to understand the thermal history and its link to process parameters. Here brief description of current ideas developed during this period. Chao et al. (1998) were one of the first researchers to publish a three-dimensional heat transfer model to predict the thermal history and the subsequent thermal stress and distortion of the work piece assuming a constant heat flux input from the tool shoulder and work piece interface. Whereas a process model for FSW also developed by Friggaard, Grong and Midling(1998), (2001) in which the heat input from the tool shoulder is assumed to be the frictional heat entirely. McClure et al.(1998) used Rosenthal equations and proposed a model to calculate temperature fields in friction stir welding. They also proved that existence of the thermocouples and holes containing thermocouples do not influence the temperature field. Chao and Qi(1999) proposed a model assuming sliding friction the cause of heat generation and used Coulomb’s law to estimate the shear or friction force at the interface. Gould and Feng (1999) also developed a thermal model to predict the temperatures of welds using the Rosenthal equations to describe a moving heat source. The heat input was given as a function of process parameters such as tool rpm and force on tool. An advanced analytical estimation of the heat generation for tools with a threaded probe to estimate the heat generation distribution was done by Colegrove(2000). The fraction of heat generated by the probe is found to be almost 20%, which concludes that the heat generation contribution is not negligible. Ulysse(2002) used a three dimensional visco-plastic modeling to model friction stir welding process. Chao et al. (2003) formulated a boundary value problem for tool and workpiece in order to study the heat transfer in friction stir welding. The remarkable result was that only about 5% heat is generated to the tool and the rest flows to the workpiece. Thus the heat efficiency in FSW (almost 95%) is very high than conventional welding processes (typically 60 to 80%). Song and Kovacevic(2003) investigated the influence of the preheating or dwell period on the temperature fields. They assumed a sliding condition and used an effective friction coefficient and experimental plunge force in the heat source expression. Chen and Kovacevic(2003) developed an input torque based thermal model for prediction of temperature in friction stir welds of Al-6061-T6 alloy.Khandkar et al(2003) used a model in which the heat produced by tool rotation and tool speed, has been associated with actual machine power input. Song and Kovacevic(2004) proposed a coupled heat transfer model of both the tool and the workpiece for FSW to include the tool penetration and pulling out phase. A moving coordinate was adopted to reduce the difficulty of modeling the heat generation due to the movement of the tool pin. Vilaca et al.(2005) developed an analytical thermal model for simulation of friction stir welding process. The model included simulation of the asymmetric heat field under the tool shoulder resulting from viscous and interfacial friction dissipation. Hwang et al.(2008) experimentally determined the thermal histories and temperature distributions in a workpiece were during FSW of butt joining process of aluminum 6061-T6. Hamilton et al. (2009) proposed a thermal model of
the FSW of aluminium alloys that incorporates heat
generation due to plastic deformation and divides the
heat flux between friction and plastic deformation
based on the ratio of the plastic energy to the total
effective energy. From the statistical analysis
Rajamanickam et al. (2009) found that the peak
temperature at weld zone is strongly influenced by the
tool rotation (Probability of 82.67%) than weld speed
and it was also observed from the thermal history that
for given weld speed, higher tool rotation resulted in
higher energy input per unit length of the weld.
Muhsin et al. (2012) showed that maximum
temperature during FSW is significantly less than the
melting temperature of 7020-T53 aluminium alloy
and the temperature at advance side is higher than
retreat side.

Say, there is a frictional stress \( \tau \) between the tool
and workpiece. Also the speed of a point on the tool
surface is \( 'w' \) and that the speed of the material due
to mass flow is \( 'v' \) at that point. The heat generated
per unit area due to friction between the tool and the
workpiece will be as stress multiplied by the relative
velocity as shown in equation 1.

\[
Q'' = \tau \cdot (w \cdot r - v) \quad (W/m^2)
\]

2.2 Plastic deformation of the metal due to the
visco-plastic mass flow:
The tool basically does some work on the
material to make it flow (i.e. plastically deform it),
this work is converted to heat. Actually the plastic
deformation causes heat generation due to the internal
friction between the various layers of metal being
deformed. The actual calculation of the heat generated
due to plastic deformation requires us to calculate the
frictional heat generated at each layer of the mass
flow. The layer closest to the tool will have maximum
velocity (let, \( v \)) and the layer farthest away from the
tool will be static or have no velocity. The frictional
heat generated between two layers with a velocity
difference of \( 'dv' \) and the frictional stress of \( \tau \)
between them will be \( \tau \cdot dv \). The situation is shown in
Figure 1.

To get the total heat generated we must integrate
this expression across the mass flow layer formed. A
simple assumption taken that the value of \( \tau \) is constant
across the layer and is equal to the frictional stress
between the tool and the workpiece. Thus with this
assumption the heat generated per unit area due to
plastic deformation can be assumed as \( W \cdot v \).

\[
Q'' = \int \tau \cdot dv = \tau \int dv = \tau \cdot v \quad (W/m^2)
\]

If we add the heat generated due to plastic
deformation and friction we get:

\[
Q'' = Q''_1 + Q''_2 = \tau \cdot w \cdot r \quad (W/m^2)
\]

Heat is also generated due to friction when the
tool is entering or plunging in the workpiece (plates in
our case). The utmost exact analysis should simulate
all these sources and also the entry of the tool. The
current analysis is a transient thermal analysis. The
analysis simulates only the thermal effects of the tool
rotation and mass flow. The thermal effects of the tool
entering the plates and exiting the plates are not
simulated. This is reasonable, as, though heat is
produced in the process of entering and exiting of the
tool (due to the friction between the tool and the
plates), it is negligible in comparison to the heat
generated in the actual friction stirring process.

The value to be given for \( \tau \) requires a deeper
look. Most analysis performed on FSW in the past
have taken the value of \( \tau = \mu P \). This approach is not
correct and requires modifications. Various analyses
had been done by the authors with the same approach.
The results were disappointing as the temperatures
achieved by the workpiece were more than the
melting point at certain locations. This is in
contradiction with the basic property of FSW being a
solid state welding process. FSW being a solid state
welding process implies that the temperatures achieved by workpiece can never be more than the melting point. The reason for this excessive temperature rise is the value of $\mu P$. This value suggests that the heat generated is proportional to consistently proportional to the vertical pressure $P$ (and thus the downward force) applied. This suggests that if the vertical pressure is increased to extremely high values the heat generated will increase proportionally and also the temperature. Thus it is incorrect to simply give the value of $\tau$ as $\mu P$. To understand the correct value of $\tau$ the following concept must be understand.

As discussed previously the contact condition at the tool material interface may be sticking or sliding. It should be observed that $\mu P$ is the maximum value that $\tau$ can attain. Also $\tau$ attains it maximum value when the contact condition is that of sliding. When the contact condition is that of sticking the value of $\tau$ will be less than $\mu P$. This can be understood by considering a simple case of two blocks in contact. When there is relative motion (sliding) between the two blocks. The friction attains it maximum value $\mu P$. If there is no relative motion the friction force is less than its maximum value.

When the temperature of the workpiece increases, its shear yield strength decreases. The shear yield strength of the material is the minimum shear stress required to yield (or extensively plastically deform) the material. Thus when the value of $\tau$ is equal to the shear strength, sticking takes place because the material is able to deform extensively and flow at the tool velocity. At higher temperature the shear strength is decreases to values lower than that of $\mu P$. Thus sticking takes place and the value of $\tau$ becomes equal to that of shear strength. The process is showed in a flowchart in figure 2.

The complete process of the change in the value of $\tau$ is summarized in the flow chart shown in figure 2. This is the reason that temperature never exceeds the melting point in FSW. As, when the temperature reaches near the melting point, the material softens and sticking starts thus reducing the value of $\tau$, which in turn reduces the heat generated, which in turn prevents further rise in temperature. As we have assumed only complete sticking or complete sliding (i.e. there is never partial sticking or partial sliding) in the current analysis, we need to identify the Temperature at which complete sticking start. Complete sticking will start at the Temperature at which $\tau$ becomes equal to the shear strength. $\tau$ will be equal to $k$ when the value of $k$ is less than $\mu P$ (the maximum value of $\tau$). To find the temperature at which $k$ becomes less than $\mu P$ we must observe the variation of $k$ with temperature. Variation of shear strength (MPa) with temperature (Kelvin) is given in table 2.

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Shear Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>589</td>
<td>9.5</td>
</tr>
<tr>
<td>644</td>
<td>6</td>
</tr>
<tr>
<td>923</td>
<td>0</td>
</tr>
</tbody>
</table>

Please note that the value of $\tau$ has been assumed to be zero at Melting Point, 923 K (this is done, as, it takes negligible shear to deform a fluid). The other two values of $k$ are legitimate lab test results. With the help of these results a best fitting function (equation no. 9) is generated which gives the values of $k$ as a function of temperature. The variation of $\tau$ with temperature is shown in figure 3.

$$k=0.0001*(\text{Temp}-923)^2$$

Equating this curve to the value of $\mu P$ we get the temperature as 717 K. Thus $k$ will be less than $\mu P$ when temperature $> 717$ K and sticking will start. Therefore $\tau$ will be

a) $\mu P = 0.3*11.2\text{MPa} = 3.36 \text{ MPa}$ till Temperature $< 717$ K (sliding) (Intersecting points)  
b) $k = 0.0001*(\text{Temp}-923)^2$ after Temperature$>717$ K (sticking)

Figure 3: Variation of $\tau$ with temperature

Linear fitting function of above two equations (i.e. equation (a) and equation (b)) (Linear regression):

$$\tau = -(0.0065.\text{Temp}) + 6 \quad (\text{MPa})$$

$\tau$ is not given into ANSYS as a constant value but as a function of Temperature. Though it is possible to find functions which fit extremely well to the points plotted, the application of loads with such a steep fall
in heat flux input make the solution difficult to converge. Thus through linear regression a best fitting linear function is generated. The value of \( \tau \) is given as this linear function of temperature. Though this linear curve is not a good fit for the points, it ensures that the temperature will not rise above the melting point and will be a more accurate simulation of a real FSW.

### 3 Boundary conditions

The current analysis aims to study the effects of process parameters on thermal history. The process parameters considered in the current analysis are rotational speed of the tool and traverse velocity of the tool. The process parameters for which simulations have been performed are shown in Table 1.

The following loads are applied to best simulate the thermal aspect of FSW. A surface heat flux has been applied to the top surface of the model to simulate the heat produced at the shoulder of the tool due to friction and plastic deformation of the material.

#### Table 2: The process parameters

<table>
<thead>
<tr>
<th>Transverse Velocities (mm/s)</th>
<th>Rotational Velocities (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>1000</td>
</tr>
<tr>
<td>2.0</td>
<td>1200</td>
</tr>
<tr>
<td>2.2</td>
<td>1400</td>
</tr>
</tbody>
</table>

The surface heat flux has been applied only to the region occupied by the tool shoulder i.e. where the value of \( r \) (distance from the center of the tool) is between 3 and 12.5 mm. As discussed earlier, the total heat generated per unit area due to both plastic deformation and friction is given by:

\[
Q'' = \tau \cdot w \cdot r \quad \text{(W/m}^2\text{)} \quad (6)
\]

Heat Generation: This load is applied to 3D volume. The value of this load is in Watt/m3. When this load is applied, a volumetric heat generation equal to the given value in magnitude is applied to the selected volume of the geometry.

A volumetric heat generation has been applied to the model to simulate the heat produced at thin pin surface of the tool due to friction and plastic deformation of the material. The volumetric heat generation has been applied only to the region occupied by the tool pin i.e. where the value of \( r \) (distance from the center of the tool) is between 0 and 3 mm. Actually the heat generated by the pin is generated at the surface of the pin and should be applied as a surface flux for best results. But it is extremely difficult to apply a surface flux at cylindrical surface inside the model, which imitates the pin surface. Thus the load has been applied as volumetric heat generation occupying the pin volume. This approximation is reasonable as the heat generated at pin surface is less than 20% of the total heat generation and the volume occupied by pin is as it is extremely small. As discussed earlier, the total heat generated per unit area due to both plastic deformation and friction is given by \( \tau \cdot w \cdot r \cdot \mu \).

Multiplying this by the area of the pin surface gives the total heat generated. But since the load is given as a volumetric heat generation (W/m3), it is important to divide the total heat generated by the volume of the pin. Thus the value of the volumetric heat generation load is:

\[
Q'' = (\tau \cdot w \cdot r) \cdot \frac{2 \pi r_p H_p}{\pi r_p^2} = 2 \cdot \tau \cdot w \text{(W/m}^3\text{)} \quad (7)
\]

Here \( \tau \) (the frictional shear stress between the pin’s side walls and the workpiece) has nothing to do with \( P \) (the vertical pressure applied). Various published papers with successful FSW simulations have taken the value of \( \tau \) to be the value of shear strength at 75% of the melting point \( (k^*) \) which is equal to 2.272 MPa in our case. This is a reasonable assumption as the metal near the pin surface is mostly in sticking condition and has sufficiently high temperatures. Thus \( \tau \) here is given into ANSYS as constant value of 2.272 MPa. A convective heat transfer has been applied to all the surfaces except the bottom surface, to simulate the effect of natural convection. From common knowledge of natural convection at room temperature the values given are: \( h = 10 \) (W/m2K). In a real FSW process the maximum heat loss from the workpiece is due to conduction of heat to the backing plate on which the workpiece rests. The effect of this heat loss has been simulated not as conduction but as a convective heat loss. Since conduction is a much more efficient method of heat transfer than convection, the value of heat transfer coefficient is given much more than the natural convection value. This ensures that the heat loss due to conduction to backing plate (simulated as convection) will be much more than natural convection i.e. \( h = 100 \) (W/m2K).

The following assumptions and notations are prerequisites to understanding the current analysis.

The tool dimensions are assumed in this present study as, \( (R_s) \) Shoulder Radius-12.5mm, \( (r_p) \) Pin Radius-3mm, \( (H_p) \) Pin Height-3mm, \( P \): This is the pressure between the tool and the workpiece. This develops as a result of the downward force applied on the tool. In this current analysis the downward force \( (F) \) is assumed to be 5.5 kN. In terms of the shoulder radius of the tool and the downward force applied the pressure between the tool and workpiece is:

\[
P = \frac{F}{A} = \frac{F}{\pi r_s^2} \quad (8)
\]

Thus, \( P = 11,200,000 \) Pa.

There are two contact conditions possible at the tool and workpiece interface: Sliding and Sticking. In sliding the velocity of the material in immediate contact with the tool is less than velocity of a point on the tool. In sticking velocity of the material in immediate contact with the tool is equal to the velocity of a point on the tool. 

\( \tau \): The frictional stress between the tool surface and the workpiece. The maximum value of \( \tau \) can be \( \mu P \).
w: This is the rotational speed of the tool, V: This is the traverse speed of the tool, v: This is the velocity of the material layer in contact with the tool, r: This is the distance of a pint from the tool axis at a particular instant.

### 3.1 Material properties

The properties of AA 6061-T6 (like most metals) vary significantly with temperature. Thus for more accurate results the properties of the materials are given as different values for different temperatures. The Table 3 gives the values of the material properties Kiralet. al. (2013) thermal conductivity and specific heat for different temperatures. The density of the material is 2700 kg/m$^3$ and is not given as temperature dependent.

<table>
<thead>
<tr>
<th>T(°C)</th>
<th>k(W/m°C)</th>
<th>C_p(J/kg°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-17.8</td>
<td>162</td>
<td>904</td>
</tr>
<tr>
<td>37.8</td>
<td>162</td>
<td>945</td>
</tr>
<tr>
<td>93.3</td>
<td>177</td>
<td>978</td>
</tr>
<tr>
<td>148.9</td>
<td>184</td>
<td>1004</td>
</tr>
<tr>
<td>204.4</td>
<td>192</td>
<td>1028</td>
</tr>
<tr>
<td>250</td>
<td>201</td>
<td>1052</td>
</tr>
<tr>
<td>315.6</td>
<td>207</td>
<td>1078</td>
</tr>
<tr>
<td>371.1</td>
<td>217</td>
<td>1104</td>
</tr>
<tr>
<td>426.7</td>
<td>223</td>
<td>1133</td>
</tr>
<tr>
<td>571.1</td>
<td>253</td>
<td>1290</td>
</tr>
</tbody>
</table>

**Table 3: Material properties of AA 6061-T6**

### 4 Results and Discussions

In the current analysis, the temperatures attained at two points, namely A and B, are considered as the primal results. For all simulations performed the point A lies on the on the central weld line and the point B lies at a distance of 14 mm from the weld line (just outside the shoulder radius). It is intuitively obvious that the maximum temperature attained at point A will also be the maximum temperature attained in the entire workpiece in the complete process. Following table 4 shows the values of maximum temperatures attained vs. rotational speeds at points A and B. Table 5 shows maximum temperatures vs. rotational speeds for point A and B respectively.

**Table 4: Numerical and experimental comparison**

<table>
<thead>
<tr>
<th>Rotational Speed (w in rpm)</th>
<th>Experimental Max Temp at point B (K)</th>
<th>Present Max Temp point B (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>593.1</td>
<td>610</td>
</tr>
<tr>
<td>1200</td>
<td>607.9</td>
<td>634.35</td>
</tr>
<tr>
<td>1400</td>
<td>627.00</td>
<td>653</td>
</tr>
</tbody>
</table>

**Table 5: Maximum Temperature vs. Rotational speed**

<table>
<thead>
<tr>
<th>Rotational Speed (w in rpm)</th>
<th>Max Temp point A (K)</th>
<th>Max Temp point B (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>698.5</td>
<td>610</td>
</tr>
<tr>
<td>1200</td>
<td>728.2</td>
<td>634.35</td>
</tr>
<tr>
<td>1400</td>
<td>752</td>
<td>653</td>
</tr>
</tbody>
</table>

Following are the maximum temperature attained vs. traverse speeds at points A and B. Figure 4 shows the temperature profile on point A and B as the tool passes by the these points at course of welding. The graph shows the rate of rise in temperature for A and B point.

**Table 6: Maximum temperature vs. tool traverse speed**

<table>
<thead>
<tr>
<th>Transverse Speed (mm/s)</th>
<th>Max Temp point A (K)</th>
<th>Max Temp point B (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>779</td>
<td>662</td>
</tr>
<tr>
<td>2.0</td>
<td>752</td>
<td>653</td>
</tr>
<tr>
<td>2.2</td>
<td>738.331</td>
<td>642.66</td>
</tr>
</tbody>
</table>

The square dotted lines shows the center line temperature attained in the welding and circular dotted line in the graph is representing the rise and fall of temperature at 14mm away from the weld line.

### 4.1 Results of sticking and sliding comparison

Temperature contour for the two contact conditions are shown in figure 5. The temperatures achieved in the sliding condition, i.e. the when the sticking phenomenon is not considered, are much more than the melting point of the material which is 923 K. This result is obviously flawed as FSW is a solid state welding process. This shows that it is essential to consider the sticking condition for a realistic FSW simulation. In the case where sticking is considered, the temperatures achieved are much more realistic Temperature time graphs of Points A, B are compared for the two contact conditions. The temperature difference are quite significance in the two cases. This emphasizes the necessity of considering the sticking phenomenon while simulating the FSW.
5 Conclusions

The following conclusions can be made from the present study:

Increasing the rotational speed of the FSW tool increases the amount of heat generation in the welding process. This is indicated by the increased temperature attained by the workpiece. This is helpful at least, from the thermal aspect of the process. This is probably caused by the increased friction heat generated. The increased plastic deformation due to high speeds can also be a cause. Thus from an isolated thermal stand point, increasing the rotational speed improves the heat generated and thus makes the weld better.

Increasing the transverse velocity of the tool reduces the temperature attained by the workpiece. This is probably because 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. Thus from an isolated thermal stand point it is better to perform the FSW process with low transverse velocities.

While simulating FSW it is important 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. Analyses have been performed, ignoring sticking, which have resulted in the temperatures exceeding the melting point of the material. This violates the basic property of FSW being a solid state welding process.

Any point in the workpiece has a similar Temperature time curve with the rate of increase being more in magnitude than the rate of decrease. This is probably because the power generated by the FSW tool is much more than the cooling offered by natural convection or the backing plate conduction.

References


