Developing an Alternative Heat Indexing Equation for FSW

An alternative heat indexing equation is proposed that considers the heat generation terms and thermal dissipation

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ABSTRACT

In friction stir welding (FSW), a nonconsumable, rotating weld tool is used to impart large shear deformations under a simultaneous compressive stress state to produce a solid-state weld joint between the former facing surfaces. The process results in a refinement of the microstructure in the stir zone (SZ) in response to the heat and plastic deformation. The peak temperature in the weldment is balanced between generation via frictional and deformational heating, and thermal dissipation. Heat index equations published in the literature do not consider the effect of thermal dissipation. The thermal dissipation is dependent on the travel velocity, weld tool geometry, and thermal properties of the workpiece and process tooling that includes the tool, spindle, and backing anvil. Maintaining a constant temperature is important in ensuring the production of high-quality welds over a range of weld schedules. This study proposes an alternative heat indexing (AHI) equation that considers not only the heat generation terms but also the thermal dissipation to ensure a constant peak temperature when modifying or extrapolating weld schedules.

KEYWORDS

Friction Stir Welding (FSW)  
Stir Zone (SZ)  
Heat Indexing Equation  
Thermal Dissipation  
Alternative Heat Indexing  
Heat Generation

Improving the accuracy of FSW model predictions and process scalability requires incorporating the influence from both the process parameters and tooling. As such, this study considers the development of a one-dimensional heat transfer model that includes the geometry of the weld tool, the thermal properties of the workpiece and tooling, and the process parameters. This model is then used as the basis for development of an alternative heat indexing equation for FSW.

Experimental Procedure

In the present study, two FSW tools, whose dimensions are summarized in Table 1, were used to produce friction stir welded panels. A cylindrical pin was used on both tools, one with a smooth surface and the other with a threaded surface. Both FSW tools used a smooth, 7-deg concave shoulder and all of the friction stir welds were made using a 2.5-deg tilt angle. bead-on-plate (BOP) friction stir welds were made along the rolling direction and center width of 150 mm wide x 610 mm long x 6.4 mm thick AA2219-T87 plates. The horizontal weld tool (HWT) at the National Aeronautics and Space Administration’s Marshall Space Flight Center (NASA-MSFC) was used to produce the friction stir welds. During the weld, continuous recordings were made of the z-axis (plunge) force, x-axis (plow) force, weld torque, spindle speed, travel velocity, and x-axis position. The weld torque was
measured with a load cell connected to the spindle with a known arm length, thus recording the actual moment that occurs about the spindle as a result of the reaction between the FSW tool and workpiece.

To evaluate the accuracy of the PHI relationship and consider the interaction of process parameters and tooling, initial process parameters were based on published values for FSW 6.4-mm-thick plates of AA2219-T87 (Refs. 8, 11). Table 2 summarizes the test matrix used in this study, which was designed using a constant PHI to consider the range of validity (Ref. 10). From reported studies (Refs. 8, 11), a PHI of 0.09 has been correlated with defect-free friction stir welds in AA2219-T87 over a range of travel velocities from 76 to 203 mm/min. For PHIs greater than 0.12, the friction stir welds were reported to show void-type defects. In this study, the travel velocity was calculated for a given spindle speed using a PHI of 0.09. The spindle speed and z-axis force were selected based on initial baseline friction stir welds to determine processing parameters to produce defect-free welds. Differences in z-axis force are attributed to differences in the shoulder diameter.

One-Dimensional Heat Transfer Model

Figure 1 shows a schematic of the heat source and sinks considered in the development of an alternative heat indexing equation. The model consists of a power generation term that incorporates the geometry of the FSW tool and process parameters, heat loss terms for conduction within the weldment and through the backing anvil and spindle, and convection required to continuously heat newly incorporated material within the stir zone (SZ). The convective heat loss is dependent on the cross-sectional area of the surface defining the SZ and travel velocity. The surface that denotes the separation of the SZ from the base material (BM) is referred to as the shear surface as illustrated in Fig. 2.

![Fig. 1 — Schematic representation of a transverse view of the heat source and sinks associated with FSW. Note the heat flow paths are represented by the arrows.](Image)

![Fig. 2 — Schematic representation of a cylindrical pin FSW tool and the shear surface separating the stir zone (SZ) from the rest of the weld.](Image)

<table>
<thead>
<tr>
<th>Table 1 — Dimensions of the Weld Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth Pin (mm)</td>
</tr>
<tr>
<td>Shoulder Diameter</td>
</tr>
<tr>
<td>Pin Diameter</td>
</tr>
<tr>
<td>Pin Length</td>
</tr>
</tbody>
</table>

In this study, the temperature ($T$) refers to the shear surface temperature, and the temperature ($T_i$) refers to a fixed ambient temperature at a distance from the source. For a cylindrical pin, the heat source is approximated as a cylinder, as shown in Fig. 3. In the development of this model, it is assumed that the heat source represents the shear surface and the shear surface is isothermal.

The heat loss terms for the model are derived from Fourier’s Law in one dimension, which is expressed in Equation 2 (Ref. 12). In the expression ($Q_n$) is the rate of heat transfer, ($k$) is the thermal conductivity of the material, ($A$) is the area through which heat flows, and $dT/dn$ is the temperature gradient with respect to distance in the direction normal to $A$.

$$Q_n = -kA rac{dT}{dn} \tag{2}$$

Power Generation

The rate at which work is performed is termed power. In FSW, power is required to rotate the weld tool in the workpiece and traverse along the weld joint. Power for a rotating object is calculated by multiplying the torque and the angular velocity, while the power for traversing longitudinally along the weld joint is calculated by multiplying the force acting in that direction by the velocity in that direction. Reported total weld power calculations for welds that did not contain defects concluded that the contributions from the tool rotating were in excess of 98% (Ref. 13). Therefore, in this study, the weld power was approximated off of the weld torque and spindle speed.

An assumption of the steady-state operation of the FSW process is made in which the contact conditions between the workpiece and FSW tool are assumed to be sticking. This is based on experimental evidence that the FSW tool/workpiece contact conditions are dominated by the sticking contact condition (Ref. 14). The weld torque ($M$) can be calculated analytically by Equation 3. Other researchers have used similar expressions to calculate the weld torque and power (Refs. 14–16). In Equation 3, ($r$) is the flow stress of the material along the shear surface and ($r$) is the distance from the tool center to the shear surface. The radius ($r$) is a function of its placement along the z-axis. If the boundary of the shear surface is not known, i.e. radius as a function of the z-axis, then the FSW tool profile can be used for an approximation. This torque multiplied by the spindle speed gives an analytical expression for calculating the weld power. For a cylindrical pin FSW tool where the shear surface is estimated as that of the
FSW tool profile, Equation 3 is multiplied by the spindle speed and solved yielding Equation 4, an expression for the weld power ($Q_g$). In Equation 4, ($R_s$) is the radius of the tool shoulder, ($R$) is the radius of the pin, ($H$) is the length of the pin, ($\omega$) is the spindle speed, and ($\tau$) is the flow stress of the material along the shear surface.

$$Q_s =\omega R_s^3 \left[ \frac{1}{3} \left( \frac{R}{R_s} \right)^3 + \frac{H}{R} \right]$$

(4)

Heat Loss Terms

As illustrated in Fig. 1, the heat losses assumed include conduction losses to the workpiece, anvil, and spindle, in addition to a convective heat loss to the workpiece. Each is briefly described in this section.

For a cylindrical heat source, the conductive losses to the workpiece ($Q_{w}$) are approximated as a radial flow of heat from the cylindrical heat source at radius ($R$) to a fixed temperature ($T_0$) at radius ($R_0$). The expression for this heat loss is given in Equation 5 where ($k_w$) is the thermal conductivity of the workpiece and ($T$) is the shear surface temperature.

$$Q_{w} = \frac{(T-T_0)}{\ln \frac{R_0}{R}}$$

(5)

Conduction losses to the anvil ($Q_{a}$) are approximated as a spherically radial flow of heat from under the bottom of the pin into a thick block of material as given by Equation 6. The radius of the bottom of the pin ($R_a$) is assumed equal to ($R$) for the cylindrical source. In Equation 6, ($k_a$) is the thermal conductivity of the anvil.

### Table 2 — Test Matrix for FSW AA2219-T87

<table>
<thead>
<tr>
<th>Spindle Speed (rev/min)</th>
<th>Travel Velocity (mm/min)</th>
<th>Forge Force (kN)</th>
<th>Weld Pitch (mm/rev)</th>
<th>Tilt Angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>46</td>
<td>17.8</td>
<td>24.5</td>
<td>0.23</td>
</tr>
<tr>
<td>300</td>
<td>102</td>
<td>17.8</td>
<td>24.5</td>
<td>0.34</td>
</tr>
<tr>
<td>400</td>
<td>180</td>
<td>17.8</td>
<td>24.5</td>
<td>0.45</td>
</tr>
<tr>
<td>500</td>
<td>282</td>
<td>17.8</td>
<td>24.5</td>
<td>0.56</td>
</tr>
</tbody>
</table>
The conduction loss to the spindle \( (Q_s) \) is approximated as a linear flow of heat in a rod. Heat travels from the shear surface temperature \( (T) \) at the shoulder through a length of rod \( (L_{sp}) \) to a fixed ambient temperature \( (T_0) \). The expression for the heat loss to the spindle is given in Equation 7. Where \( (k_{sp}) \) and \( (r_{sp}) \) refer to the effective spindle thermal conductivity and radius, respectively.

\[
Q_s = 2\pi r_s \frac{k_{sp}}{r_{sp}} (T - T_0) \tag{6}
\]

As the tool advances during the weld, cooler material enters the front of the weld while hotter material is deposited in the wake of the weld. This gives rise to convective heat loss. The convective heat loss is dependent on the power required to heat material passing through the cross section of the shear surface from ambient to that of the shear surface. As with the case of power generation, the cross section of the pin profile may be substituted to make an approximation if the shear surface profile is not known. The expression for the convective heat loss \( (Q_v) \) considering a cylindrical profile is given in Equation 8. Where \( (2RH) \) describes the cross-sectional area, \( (V) \) refers to the travel velocity, and \( (\rho c) \) refers to the volumetric heat capacity of the workpiece material.

\[
Q_v = 2\pi RH \frac{\rho c}{V} (T - T_0) \tag{8}
\]

Theoretical Estimation of the Peak Temperature

It is assumed that FSW is a steady-state process, there is no storage of energy, and the shear surface is isothermal. Additionally, it is assumed all of the mechanical power is converted into thermal energy, and efficiency factors for the loss terms are neglected. With the present assumptions, the conservation of energy is given by Equation 9.

\[
Q = k_{sp} \frac{L_{sp}}{r_{sp}} (T - T_0) \tag{9}
\]

| Table 3 — Percent Difference Between the Model and Experimental Weld Power and Weld Torque |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Smooth Surface FSW Tool | Weld Pitch (mm/rev) | Power Difference (%) | Torque Difference (%) | Smooth Surface FSW Tool | Weld Pitch (mm/rev) | Power Difference (%) | Torque Difference (%) |
|                  |                  |                  |                  |                  |                  |                  |                  |
|                  | 0.23             | 0.1              | 0.1              |                  |                  |                  |                  |
|                  | 0.34             | 1.3              | 1.3              |                  |                  |                  |                  |
|                  | 0.45             | 10.9             | 10.9             |                  |                  |                  |                  |
|                  | 0.56             | 18.4             | 18.4             |                  |                  |                  |                  |
In addition to the relationships between the processing parameters and heat loss terms, the shear stress as a function of temperature needs to be defined. A linear approximation, Equation 10, is used that captures thermal softening with increasing temperature with a lower bound of zero flow stress at the melting temperature. In Equation 10, \( \frac{m \tau}{T_m} \) is the change in shear stress with respect to temperature in the near melting regime, \( T_m \) is the melting temperature of the workpiece, and \( T \) is the shear surface temperature.

\[
\tau = m \left( T_m - T \right) \quad (10)
\]

Figure 4 shows macrographs of the longitudinal exit hole verifying significant shoulder contact was maintained at conditions of 0.23 and 0.34 mm/rev. Thus, the value of \( m \) was found from the torque values measured at these conditions. Since it was assumed that there was no loss of shoulder contact and sticking contact conditions were experienced for these welds, any reduction in the shear surface was deemed negligible.

After applying the energy balance of Equation 9 and the relationship outlined in Equation 10, a theoretical expression for the shear surface temperature can be found. Equation 11 is the expression for the shear surface temperature using the cylindrical source expressions.

\[
T = \frac{2 \pi k R \frac{H}{c} + 2 \pi R a}{\ln \frac{R_o}{R}} + \frac{k \pi R^2}{L_{sp}} + 2RH'pc + 1
\]

\[
2m \omega \pi R^3 \left( \frac{1}{3} \frac{R_x}{R} + \frac{H}{R} \right)
\]

Discussion and Results

Based on the development of a one-dimensional heat transfer model, the shear surface temperature can be theoretically calculated based on the process pa-
parameters, geometry of the FSW tool, and thermal properties of the workpiece and tooling. Utilizing the geometry of the smooth surface FSW tool described in Table 1 and workpiece material properties for AA2219-T87, the shear surface temperature is calculated using Equation 11 for a range of travel velocities at different weld pitches.

Because direct measurements of the shear surface temperature were not obtained during this study, only the weld power can be compared. Thus, from the calculated temperature, the weld power can be determined from Equation 4 with the corresponding specific energy obtained by dividing the weld power by the travel velocity.

Figures 5 and 6 show the weld power vs. the travel velocity and the specific weld energy vs. the travel velocity, respectively, for different weld pitches. In Fig. 5, as the travel velocity is increased, the weld power also increases. These results can be explained by a conceptual heat model (Ref. 9) in which increased travel velocity brings material with a higher flow stress into the shear surface, thereby increasing the weld torque and, hence, power. These results and trends are in agreement with other published trends (Ref. 17).

Figures 7 and 8 compare the weld power and weld torque, respectively, for the calculated vs. experimental values using the smooth surface FSW tool. Similarly, Figs. 9 and 10 are the same type of graphs for the threaded surface FSW tool. At the lower weld pitches, there is good agreement. The one-dimensional heat transfer model predicts increasing weld power with increasing weld pitch. Since the weld pitch is based on the ratio of travel velocity to spindle speed, this correlates with increased travel velocity. Other studies have shown a similar correlation between increases in travel velocity and increases in weld power (Ref. 17). The torque calculations predict a decrease with increased spindle speed, regardless of travel velocity, similar to other published results (Ref. 9, 18).

The percent differences between the model and experimental weld power and weld torque are shown in Table 3. Equation 12 was used to calculate the percent difference with good agreement exhibited at the lower weld pitches.

$$\% \text{Diff} = \frac{\text{Value}_{\text{model}} - \text{Value}_{\text{expt}}} {\frac{\text{Value}_{\text{model}} + \text{Value}_{\text{expt}}}{2}}$$ (12)

To evaluate the changes in accuracy of model predictions between the lower and higher values of weld pitch, macrographs were made of all longitudinal views of the exit hole as shown in Figs. 11 and 12. At the higher weld pitches of 0.45 and 0.56 mm/rev, a loss of shoulder contact with the workpiece is observed for both the smooth and threaded surface FSW tools. If the FSW tool experiences a loss of shoulder contact, then the shearing surface decreases and less power is required to rotate the FSW tool. Repeating the model calculations and using a reduced effective shoulder radius equal to the pin radius resulted in better agreement at the higher weld pitches as summarized in Table 4.

### Alternative Heat Index

While the PHI has been used to conceptualize the heat input in a FSW, this study demonstrates its inaccuracy at maintaining a constant heat input over a range of process parameters. The constant PHI value used in this study to guide the selection of a range of processing parameters resulted in differences observed in the weld power. This is understandable as the PHI does not capture the effects of different weld tools, nor does it consider interactions with the backing anvil and spindle. To resolve this discrepancy, an AHI is proposed. Starting from the energy balance given in Equation 9, the appropriate expressions for the cylindrical FSW tool and associated heat losses are applied, and an AHI equation is formed. The utility of this equation is in its ability to predict the complementary process parameter, when one of them is varied, to maintain a constant temperature in the shear surface. It also provides the opportunity to predict process parameters to maintain a similar temperature when changing FSW tooling, e.g., anvil, spindle, etc. The expression for the AHI equation using the cylindrical terms is given in Equation 13, where \( T - T_0 \) is the temperature rise in the shear surface, and \( \tau \) is the flow stress of the material in the shear surface. When determining process parameter changes while maintaining a constant temperature rise, the shear flow shear stress \( \tau \) will be constant. When using the expression for an AHI the temperature rise divided by the shear flow stress becomes a constant value, that is the AHI.

$$AHI = \frac{(T - T_0)}{\tau} = A + \frac{\omega}{B + C + D + EV}$$ (13)

$$A = 2\pi R \left[ \frac{R_k^3}{3} + \frac{H}{R} \right]$$

$$B = \frac{2\pi k H}{R}$$

$$C = 2\pi R k_a$$

$$D = \frac{k_p \pi^2 R_p^2}{L_p}$$

$$E = 2RH \rho c$$

Equation 13 can be further simplified to isolate the process parameters of spindle speed \( \omega \) and travel velocity \( V \). In doing so, the expression ends up with two terms, one of which largely encompasses attributes of the FSW tool related to power generation. The other term largely encompasses the attributes related to the heat loss terms. This equivalent expression is shown in Equation 14.

$$AHI = \frac{(T - T_0)}{\tau} = A + \frac{\omega}{B + V}$$ (14)

$$A = \frac{\pi R^2}{H \rho c_p} \left[ \frac{1}{R} + \frac{R_k^3}{3} + \frac{H}{R} \right]$$

$$B = \frac{\pi R k_a^2}{\rho c_p} \left( \frac{k_p \pi^2 R_p^2}{L_p} \right)$$

$$C = \frac{k_a}{R}$$

$$D = \frac{R_k^3}{3} + \frac{H}{R} + \frac{k_p \pi^2 R_p^2}{2L_p R H}$$

### Conclusions

The initial process parameters were selected based on a constant PHI expression...
taken from FSW literature (Ref. 10). However, for each corresponding tool used in this study, variations were seen in the process parameter window that resulted in defect-free welds and in their weld properties. Using a one-dimensional heat transfer model, a method is proposed for calculating process parameters that takes into account the specific tool design.

Certain assumptions were made in the formulation of the model that impact the model behavior and need to be taken into consideration when using the theory to explain the process of FSW. The model is based on the sticking condition and the presence of a constant shear surface area. If a significant loss of shear surface area occurs, there will inevitably be a deviation from the model calculations and experimental observations. Thus, this model can be reversely applied to determine if there is a loss of shear area, which might indicate slipping and warrant inspection of the weld.

This theory is used to determine the shear surface temperature. If upper and lower bounds for this temperature are chosen, the model could conceivably be used to determine the processing parameters that will produce shear surface temperatures in that region. However, in the present form, the model cannot predict the required temperature. That will be dependent on the metallurgical properties of the material being welded.

In a simplified form, the model can be used to develop an alternative heat indexing equation. This equation should allow for more accurate scaling of process parameters as it takes into consideration the effects of the FSW tool geometry and other tooling. In the simplified forms, the equations can be used to determine the corresponding process parameter, \( \theta_A \) or \( \theta_B \), when one is changed to maintain a constant shear surface temperature.

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References


AWS Debuts Careers in Welding Trailer

The AWS Careers in Welding Trailer offers many attractive features to get young people excited about welding industry careers.

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- Welding scholarship information.

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