Friction Stir Welding

Introduction

Manufacturers use a modern welding method called friction stir welding to join aluminum plates. This model analyzes the heat transfer in this welding process. The model is based on a paper by M. Song and R. Kovacevic (Ref. 1).

In friction stir welding, a rotating tool moves along the weld joint and melts the aluminum through the generation of friction heat. The tool's rotation stirs the melted aluminum such that the two plates are joined. Figure 3-17 shows the rotating tool and the aluminum plates being are joined.

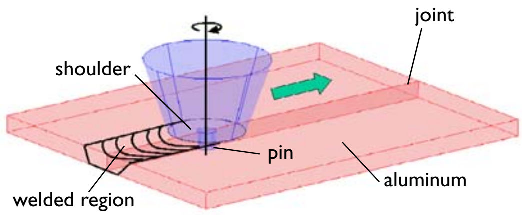

Figure 3-17: Two aluminum plates being joined by friction stir welding.

The rotating tool is in contact with the aluminum plates along two surfaces: the tool's *shoulder*, and the tool's *pin*. The tool adds heat to the aluminum plates through both interfaces.

During the welding process, the tool moves along the weld joint. This movement would require a fairly complex model if you want to model the tool as a moving heat source. This example takes a different approach that uses a moving coordinate system that is fixed at the tool axis (Ref. 1 also takes this approach). After making the coordinate transformation, the heat transfer problem becomes a stationary convection-conduction problem that is straightforward to model.

The model includes some simplifications. For example, the coordinate transformation assumes that the aluminum plates are infinitely long. This means that the analysis neglects effects near the edges of the plates. Neither does the model account for the stirring process in the aluminum, which is very complex because it includes phase changes and material flow from the front to the back of the rotating tool.

Model Definition

The model geometry is symmetric around the weld. It is therefore sufficient to model only one aluminum plate. The plate dimensions are 120 mm×102 mm×12.7 mm, surrounded by two infinite domains in the x direction. Figure 3-18 shows the resulting model geometry:

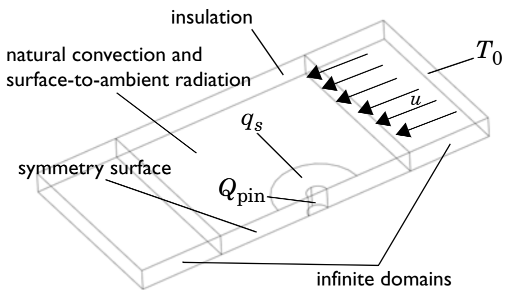

Figure 3-18: Model geometry for friction stir welding.

The following equation describes heat transfer in the plate. As a result of fixing the coordinate system in the welding tool, the equation includes a convective term in addition to the conductive term. The equation is

$$\nabla \cdot (-k\nabla T) = Q - \rho C_p \mathbf{u} \cdot \nabla T$$

where k represents thermal conductivity, ρ is the density, C_p denotes specific heat capacity, and $\mathbf{u}$ is the velocity.

The model sets the velocity to $u = 1.59 \cdot 10^{-3}$ m/s in the negative x direction.

The model simulates the heat generated in the interface between the tool's pin and the workpiece as a surface heat source (expression adapted from Ref. 2):

$$q_{\mathrm{pin}}(T) = \frac{\mu}{\sqrt{3(1+\mu^2)}} r_{\mathrm{p}} \omega \bar{Y}(T) \quad (\mathrm{W/m^2})$$

Here μ is the friction coefficient, r_{p} denotes the pin radius, ω refers to the pin's angular velocity (rad/s), and $\bar{Y}(T)$ is the average shear stress of the material. As indicated, the average shear stress is a function of the temperature; for this model, you approximate this function with an interpolation function determined from experimental data given in Ref. 1 (see Figure 3-20).

Additionally, heat is generated at the interface between the tool's shoulder and the workpiece; the following expression defines the local heat flux per unit area (W/m^2) at the distance r from the center axis of the tool:

$$q_{\text{shoulder}}(r, T) = \begin{cases} (\mu F_{\text{n}}/A_s)\omega r & ; T < T_{\text{melt}} \\ 0 & ; T \geq T_{\text{melt}} \end{cases}$$

Here F_n represents the normal force, A_s is the shoulder's surface area, and T_{melt} is aluminum's melting temperature. As before, μ is the friction coefficient and ω is the angular velocity of the tool (rad/s).

Above the melting temperature of aluminum, the friction between the tool and the aluminum plate is very low. Therefore, the model sets the heat generation from the shoulder and the pin to zero when the temperature is equal to or higher than the melting temperature.

Symmetry will be assumed along the weld joint boundary.

The upper and lower surfaces of the aluminum plates lose heat due to natural convection and surface-to-ambient radiation. The corresponding heat flux expressions for these surfaces are

$$q_{\text{up}} = h_{\text{up}}(T_0 - T) + \varepsilon\sigma(T_{\text{amb}}^4 - T^4)$$
$$q_{\text{down}} = h_{\text{down}}(T_0 - T) + \varepsilon\sigma(T_{\text{amb}}^4 - T^4)$$

where h_{up} and h_{down} are heat transfer coefficients for natural convection, T_0 is an associated reference temperature, ε is the surface emissivity, σ is the Stefan-Boltzmann constant, and T_{amb} is the ambient air temperature.

The modeling of an infinite domain on the left-hand side, where the aluminum leaves the computational domain, makes sure that the temperature is in equilibrium with the temperature at infinity through natural convection and surface-to-ambient radiation. You therefore set the boundary condition to insulation at that location.

You can compute values for the heat transfer coefficients using empirical expressions available in the heat-transfer literature, for example, Ref. 3. In this model, use the values $h_{\text{up}} = 12.25$ W/(m^2·K) and $h_{\text{down}} = 6.25$ W/(m^2·K)

Results and Discussion

Figure 3-19 shows the resulting temperature field. Consider this result as what you would see through a window fixed to the moving welding tool.

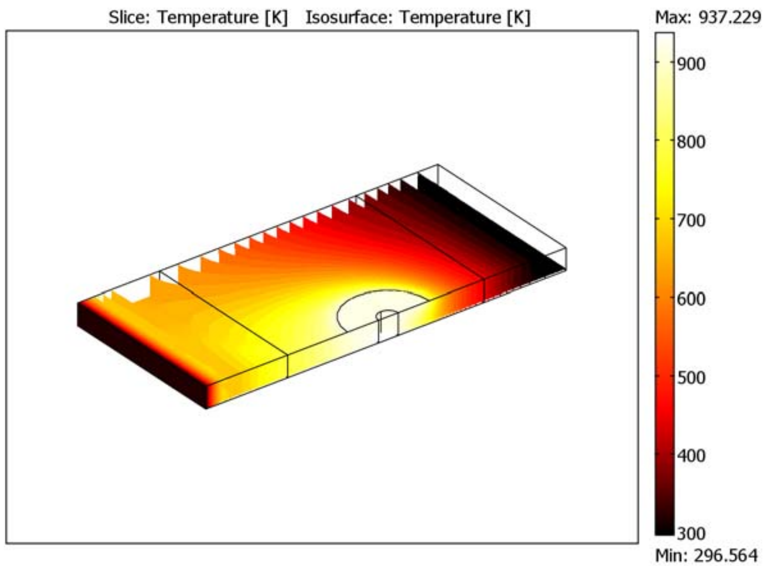

Figure 3-19: Temperature field in the aluminum plate.

The temperature is highest where the aluminum is in contact with the rotating tool. Behind the tool, the process transports hot material away, while in front of the tool, new cold material enters.

References

1. M. Song and R. Kovacevic, *International Journal of Machine Tools & Manufacture*, vol. 43, pp. 605–615, 2003.

2. P. Colegrove and others, "3-dimensional flow and thermal modelling of the friction stir welding process," Proceedings of the 2nd International Symposium on Friction Stir Welding, Gothenburg, Sweden, 2000.

3. A. Bejan, *Heat Transfer*, Wiley, 1993.