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**PROCESS MODEL FOR FRICTION STIR WELDING**

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## INTRODUCTION

Friction stir welding (FSW) is a relatively new process being applied for joining of metal alloys. The process was initially developed by The Welding Institute (TWI) in Cambridge, UK, (Dawes, 1995). The FSW process is being investigated at NASA/MSFC as a repair/initial weld procedure for fabrication of the super-light-weight aluminum-lithium shuttle external tank.

The FSW investigations at MSFC were conducted on a horizontal mill to produce butt welds of flat plate material, Figure ???. The weldment plates are butted together and fixed to a backing plate on the mill bed. A pin tool is placed into the tool holder of the mill spindle and rotated at approximately 400 rpm. The pin tool is then plunged into the plates such that the center of the probe lies at one end of the line of contact between the plates and the shoulder of the pin tool penetrates the top surface of the weldment. The weld is produced by traversing the tool along the line of contact between the plates. A lead angle allows the leading edge of the shoulder to remain above the top surface of the plate.

Dawes and Thomas (1996) list the major advantages and disadvantages of friction stir welding. When properly conducted, friction stir welding is a solid state process. The material in the weld region is plasticized but remains below its melting temperature. This is the main advantage of FSW when applied to joining aluminum-lithium alloys. Since FSW is a solid state process, the problems associated with the phase change and resolidification are eliminated. The mechanical properties of friction stir welded joints have proven to be at least as good as, and in most instances better than, fusion welded joints. The fracture strength, elongation at fracture and therefore total energy absorbed, of FSW joints are improved as compared with fusion welded joints.

The main disadvantage of friction stir welding is the reaction loads which must be accommodated in the tooling and fixturing. Conventional fusion welds require fixturing of the weldment for alignment only. There are no loads produced between the welding tool and the weldment. However, with FSW, substantial loads are produced between the pin tool and the weldment. These loads must be reacted by both the fixturing which holds the weldment and the tooling used to locate the pin tool.

## PROCESS MODEL

The goal of the process model is to develop the relationships between the dependent and independent parameters involved in FSW. The independent parameters are the pin tool rotational and travel speeds, the pin tool probe and shoulder penetration depths, and the lead angle. The dependent parameters are the axial and transverse loads on the pin tool and the temperature of the weld material. The model developed here consists of three basic aspects, a plasticity model of the parent material, energy balance within the weld region and mechanical equilibrium of the material within the weld region. A one dimensional model is developed with variations in the radial dimension only considered. It is assumed that the mechanical properties and temperature profile are independent of the coordinate along the material thickness. A schematic representation of the basic model is presented in Figure ??.

In modeling the process, it is assumed that the flow shear  $\tau_f$  dependency on temperature can be defined as

$$\tau_f = a(T - T_m)^2 \quad (1)$$

where  $T$  is the local temperature of the material and  $T_m$  is the melting temperature of the material.

An energy balance is applied to account for mechanical and thermal energy. Figure ?? represents the mechanical and thermal energy flow for a differential element within the weldment plate. Mechanical energy is introduced into the weld process through the rotating pin tool. This mechanical energy is expended in plasticizing the material and heat generation. The energy balance applied to the differential element shown, leads to the equation

$$\frac{dT}{dr} = r\omega \left( \frac{\tau_f}{k} \right) - \left( \frac{1}{r} \right) \left( \frac{A}{k} \right) \quad (2)$$

where  $r$  is the radial coordinate,  $\omega$  is the local rotational speed,  $k$  is the thermal conductivity, and  $A$  is a constant.

The torque produced by the shear forces induced on the radial faces of the differential element must balance in order for mechanical equilibrium to be maintained, Figure ?. This balance leads to a definition for the distribution of  $\tau_f$  over the plastic region

$$\tau_f = \tau_R \left( \frac{R}{r} \right)^2 \quad (3)$$

where  $R$  is the radius of the pin tool probe, and  $\tau_R$  represents the flow shear at this boundary.

Equating the definitions for the flow shear  $\tau_f$  given in Equations 1 and 3 results in an equation for the temperature distribution within the plastic region.

$$T = T_m - \sqrt{\frac{\tau_R}{a}} \left( \frac{R}{r} \right) \quad (4)$$

The temperature gradient along the radial coordinate is given by the derivative with respect to  $r$  of Equation 4

$$\frac{dT}{dr} = (T_m - T_r) \frac{R}{r^2} \quad (5)$$

where the definition  $\tau_R = a(T_m - T_R)^2$  is used.

Equating the right hand sides of Equations 2 and 5, and using the boundary condition that  $\omega = \Omega$  at  $r = R$ , we can define the constant  $A$  and derive the equation

$$\omega = \Omega - \frac{k(T_m - T_R)}{\tau_R R^2} \left[ 1 - \frac{R}{r} \right] \quad (6)$$

At the outer boundary of the plasticized region,  $r = R_p$  we can apply the boundary condition  $\omega = 0$  to obtain the relationship

$$\frac{R_p}{R} = \frac{k}{k - R^2 \Omega a (T_m - T_R)} \quad (7)$$

Applying the boundary conditions for the transfer of thermal energy results in a conflict which must be resolved. At the pin tool boundary  $r = R$ , the heat transfer from the plastic region into the pin can be defined with the use of Equation 5 as

$$Q_R = -2\pi kh(T_m - T_R) \quad (8)$$

At the boundary of the plastic zone, the heat transfer from the plastic zone is defined as

$$Q_{p1} = -2\pi kh(T_m - T_r) \frac{R}{R_p} \quad (9)$$

However, this results in heat flow from the environment into the plastic region, which seems contrary to the physical situation.

For a given radius  $R_o$  into the environment surrounding the plastic region, sufficiently distant from the plastic region, we have

$$r \left( \frac{\partial T}{\partial r} \right) = C \quad (10)$$

$$T - T_o = -C \ln \left( \frac{R_o}{R} \right) \quad (11)$$

The heat transfer into the environment at the boundary  $r = R_p$  can therefore be expressed as

$$Q_{p2} = \frac{2\pi hk(T_p - T_o)}{\ln \left( \frac{R_o}{R_p} \right)} \quad (12)$$

This represents heat transfer away from the boundary at  $r = R_p$  into the environment. Equations 9 and 12 each represent heat flow away from the boundary at  $r = R_p$ . There is no heat source at this boundary. Therefore, conduction of heat away from this boundary in both radial directions produces the conflict mentioned above. One possible explanation, is that this phenomenon involves a time dependent oscillation at the plastic region boundary which must be incorporated into the model.

If we assume no heat loss through the pin tool and allow a constant temperature distribution across the plastic region,  $T_m \approx T_R \approx T_p$ , we can balance the mechanical energy input at the pin tool with the thermal energy conducted into the environment.

$$\tau_R(2\pi Rh)R\Omega = 2\pi hk \left( \frac{T_r - T_o}{\ln \frac{R_o}{R_p}} \right) \quad (13)$$

$$\tau_R = \frac{k(T_m - T_o)}{R^2\Omega \ln \frac{R_o}{R_p}} \quad (14)$$

With the derivation of these relationships and the assumptions stated above, the following equations can be derived to relate the input requirements to the independent parameters.

The mechanical moment  $M$  and energy input  $M\Omega$  required to rotate the pin tool are given as

$$M = \frac{2\pi hk(T_m - T_o)}{\Omega \ln \frac{R_o}{R_p}} \quad (15)$$

$$M\Omega = \frac{2\pi hk(T_m - T_o)}{\ln \frac{R_o}{R_p}} \quad (16)$$

The force  $F$  and energy  $FV$  required to traverse the weld at speed  $V$  are given as

$$F = \frac{4hk(T_m - T_o)}{R\Omega \ln \frac{R_o}{R_p}} \quad (17)$$

$$FV = \frac{4hk(T_m - T_o)}{R\Omega \ln \frac{R_o}{R_p}} V \quad (18)$$

The ratio of transverse energy required to rotational energy required is given as

$$\frac{FV}{M\Omega} = \frac{2V}{\pi R\Omega} \quad (19)$$

## CONCLUSIONS

The work presented here is the first attempt at modeling a complex phenomenon. The mechanical aspects of conducting the weld process are easily defined and the process itself is controlled by relatively few input parameters. However, in the region of the weld, plasticizing and forging of the parent material occurs. These are difficult processes to model. The model presented here addresses only variations in the radial dimension outward from the pin tool axis. Examinations of the grain structure of the weld reveal that a considerable amount of material deformation also occurs in the direction parallel to the pin tool axis of rotation, through the material thickness. In addition, measurements of the axial load on the pin tool demonstrate that the forging affect of the pin tool shoulder is an important process phenomenon. Therefore, the model needs to be expanded to account for the deformations through the material thickness and the forging affect of the shoulder. The energy balance at the boundary of the plastic region with the environment required that energy flow away from the boundary in both radial directions. One resolution to this problem may be to introduce a time dependancy into the process model, allowing the energy flow to oscillate across this boundary. Finally, experimental measurements are needed to verify the concepts used here and to aid in improving the model.

## REFERENCES

Dawes, C.J., "An Introduction to friction stir welding and its development", *Welding and Sheet Metal Fabrication*, Volume 63, Number 1, pp. 13-16, January 1995.

Dawes, C.J. and Thomas, W.M., "Friction Stir Process Welds Aluminum Alloys", *Welding Journal*, Volume 75, Number 3, pp. 41-45, March 1996.

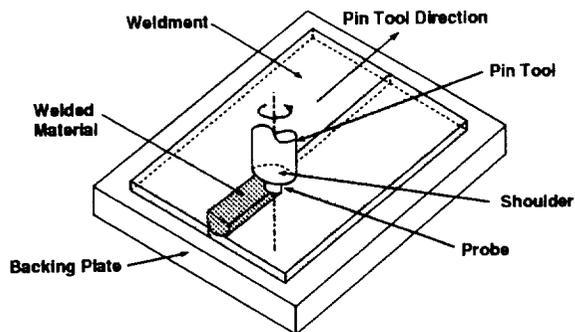


Figure 1. FSW schematic.

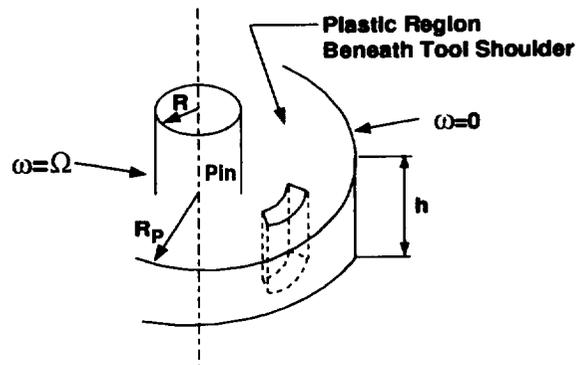


Figure 2. Basic model of FSW

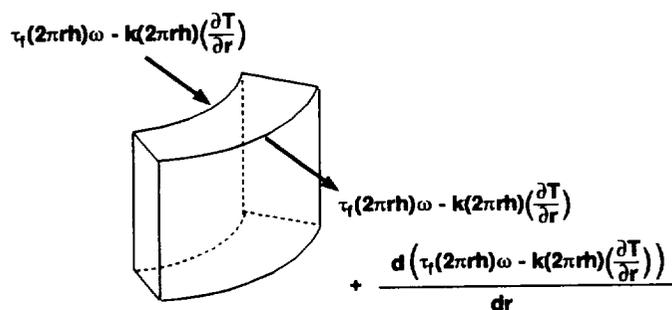


Figure 3. Energy balance.

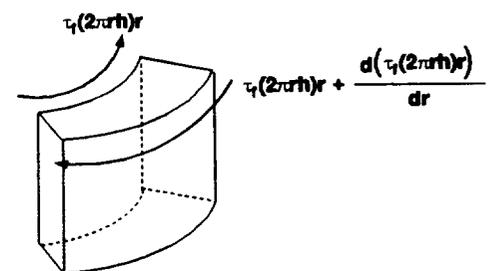


Figure 4. Mechanical equilibrium.

