Non-adiabatic shearing in Friction Stir Welding

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Abstract

A coupled model of the deformation and heat transfer in Friction Stir Welding (FSW) is presented and general expressions are obtained. These expressions are useful to understand FSW in well known alloys such as aluminum-base ones and extrapolate that understanding to higher temperature alloys. The methodology consists of determining asymptotic regimes from which to generate scaling laws. In the analysis of this problem, a threadless pin is considered and the effects of the pin and shoulder are separated. The thickness, temperature, and shear rate of the region surrounding the rotating pin are predicted using an ordering analysis inspired in the boundary layer analysis in fluid mechanics. The model presented helps understand the torque, temperatures , and deformation history of the material near the rotating pin, but it does not address the mechanical mixing occurring behind the pin. Predictions of torque, temperature, and shear region thickness agree with experiments.

Introduction

Modeling of FSW is radically different than modeling of fusion welding process, since it happens completely in the solid state. Two particular challenges stand out: First, materials properties are not well known at the high temperatures, strain rates, and strains involved in FSW. Second, the process is inherently coupled, and softening in the Heat and Deformation Affected Zone (HDAZ) is directly related to the heating, and the heating is due to the extreme plastic deformation.

This paper introduces a novel approach based on scaling theory [1, 2] in which the heat transfer problem and the deformation problems are considered simultaneously. The problem is divided in two regions in contact with each other, where asymptotic solutions are found. One of the regions is the HDAZ, which will yield the "inner solution," and the other region is the substrate, which will yield the "outer solution." Both solutions are matched through the temperature at their common boundary. To some extent, this approach resembles the analysis of the boundary layer in fluid mechanics.

Coupled Thermal and Mechanical Analysis

The simplified system considered (two-dimensional, no shoulder, cylindrical threadless pin) and the temperature distribution along the longitudinal axis are illustrated schematically in Figure 1. When the thickness of the HDAZ is much smaller than the tool radius ($\delta \ll a$), the circumferential Peclet number is very large ($\omega a^2/\alpha \gg 1$), and the tangential velocity is much larger than the translation velocity ($V_T = \omega a \gg V$), the problem can be divided in an inner and outer region. This is typically the case of FSW.

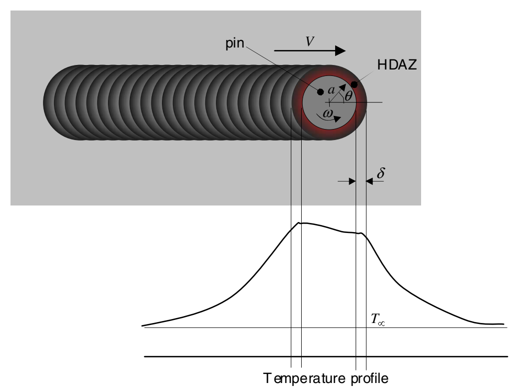

Figure 1: Schematic of FSW considered

<u>Heat and Deformation in the HDAZ</u>

The hypotheses stated imply that properties in the HDAZ are relatively independent on the position θ around the perimeter of the pin. Thus, the analysis of the HDAZ can be further simplified as the one-dimensional problem of a semi-infinite solid whose face is being sheared away. The corresponding temperature and deformation rate profiles are illustrated in Figure 2

<u>Deformation in the HDAZ</u> Assuming no-slip condition at the pin/substrate interface, a relationship between the tool tangential velocity and HDAZ properties can be ob-

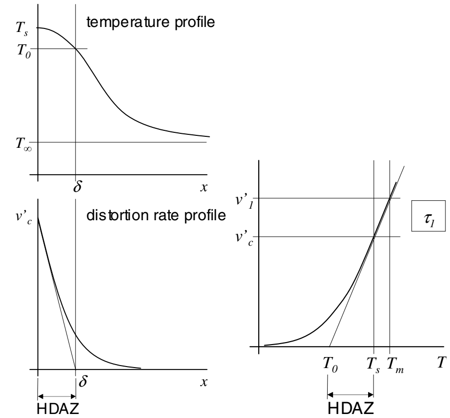

Figure 2: Left: Temperature and distortion rate profiles in the HDAZ. Right: Constitutive behavior of base metal

tained:

$$V_T = \int_0^\infty v' dx = \frac{2}{3} v'_c \delta \quad (1)$$

where v'_c is the maximum distortion rate in the HDAZ. Static equilibrium indicates that the shear stress τ should be constant through the HDAZ. The constitutive behavior considered is $v'_c = A\tau^n \exp(-B/T)$ (Figure 2), and at the typical temperatures for FSW it can be approximated as

$$v'_c \approx v'_1 (\tau/\tau_1)^n \Delta T_s / \Delta T_m \quad (2)$$

where $\Delta T_s = T_s - T_0$, $\Delta T_m = T_m - T_o$, $T_0 = T_m(1 - T_m/B)$, T_s is the temperature at the pin/substrate interface, and T_m is the solidus temperature of the alloy. The variables v'_1 and τ_1 are constants with more practical units than A. For an arbitrary τ_1: $v'_1 = A\tau_1^n \exp(-B/T_m)$. The isotherm at T_0 will be considered the limit between in HDAZ and base plate, since it roughly divides the region of high deformation rate from the undeformed region.

Heat in the HDAZ With the hypotheses stated, heat conduction is dominant across the HDAZ, obeying the equation $T" + q/k = 0$, with boundary conditions $T'(0) \approx 0$, and $T(\delta) = T_0$. The second term in the differential equation corresponds to heat generation from plastic deformation: $q = \eta\tau v'$. The efficiency η considers heat losses through the tool, and potential energy stored in the material which was not released as heat. Scaling of this differential equation yields

$$\delta^2 = 2k\Delta T_s / (\eta \tau v'_c) \quad (3)$$

Heat in the Substrate

Typical FSW problems correspond to the "slow moving heat source" type, where the isotherms are approximately circular. In this case, a point heat source on a thin plate is a reasonable approximation to the heat transfer problem, since the circular isotherms are a natural match for the circular tool. The point heat source solution neglecting the small variations with θ is [3]:

$$\Delta T_0 = T_0 - T_\infty = (\eta V_T \tau a/k) \exp(-Pe) K_0(Pe) \quad (4)$$

where k is the heat conductivity of the substrate, $Pe = Va/(2\alpha)$, and K_0 is the modified Bessel function of the second kind and order zero.

Results and Discussion

Equations 1 to 4 constitute a system of four equations with four unknowns: τ, δ, v'_c, and ΔT_s. These estimations were tested by considering typical parameters for FSW and material properties for aluminum alloys 2024 and 6061 from [4]. For FSW of 1/4" thick 2024 plate, with a pin of diameter 1/4", the following process parameters were used: V=15 ipm and 550 rpm (η=90%). The proposed model yielded a torque of 205 in-lbf, a thickness of HDAZ of 0.45 mm, and a maximum temperature of the metal of 499^{o}C. For FSW of a similar plate of 6061 with a similar tool, the parameters considered were: V=18 ipm and 1100 rpm. In this case, the calculated torque was 170 in-lbf, the thickness of HDAZ was 0.41 mm, and a maximum temperature of the metal was 579^{o}C.

The results obtained are of the correct order of magnitude, with the torque values probably overestimated, and the thickness of the HDAZ probably underestimated. Lower efficiencies improve this predictions, although they might not be typical of FSW of aluminum. Future work will consist of refining and testing the model in a variety of alloy systems, and attempting to predict optimal parameters for the FSW of high melting temperature alloys.

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