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Mechanistic Models of Friction Stir Welding

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Mechanistic Models of Friction Stir Welding
Short Report

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Purpose:

This report is submitted in partial fulfillment of the requirements of NASA's Summer Faculty Fellowship program. Due to the length restrictions, it should be considered only an extended abstract. The full report was submitted to my NASA colleague, Arthur C. Nunes, EH23.

Background:

Friction stir welding is a welding process developed at The Welding Institute (TWI) in England. The method uses very large strain plastic deformation of the material to join two pieces of metal together. The material is deformed using a tool which is forced between the two pieces which rotates causing a bond. Beyond this, very little is actually known although many people working in the field are willing to speculate on the detailed mechanisms involved. Some measurements made using sacrificial thermocouples at the weld joint indicate that the maximum temperature during the weld process is on the order of 370C - well below the melting temperature of the material. However, at this temperature, the material properties are highly temperature dependent, and the yield stress is approximately an order of magnitude less at this temperature than it is at room temperature.

As expected, there are many interpretations of the physical mechanisms occurring during the weld process. Although there is very little published concerned with FSW, some of the anecdotal theories will be described. One describes the primary mechanism as frictional heating at the front of the tool caused by slip between the tool and the material (Boeing). At elevated temperatures, the weld material becomes soft and deforms around the tool but not essentially altered by the tool rotation, similar to an extrusion. As the material meets again at the rear of the tool, the temperatures and pressures are sufficient to cause the material to bond. All other structures seen are secondary and unimportant.

Another theory examined last summer at NASA's Marshall Space Flight Center (MSFC) was that there was no slip between the tool and the material resulting in a rotating mass of plastic weld material traveling at a variety of angular velocities - the greatest at to tool surface diminishing to zero at the outer edge of the plastic mass surrounding the tool. This conceptual model was followed by simplified calculations which showed that the balance of moments through the weld plug was not possible under steady state conditions and realistic temperature profiles. This led to some consideration of a quasi-steady oscillating process. Later when force measurements became available some models were modified and new ones were proposed.

Mixed Zone Model (MZ):
The difficult job of proposing and evaluating models is made much easier by the experimental work currently being done at MSFC. An earlier model assumed that the weld material surrounding the pin tool was a continuously deforming 'pool' of material. An analysis of the required force balance is provided by Nunes, 1996. The first step is to assume a shear stress - temperature relationship,

$$\tau = a(T - T_m)^n$$

where $\tau\left[\frac{F}{L^2}\right]$ is the flow stress, T is the local temperature, T_m [C] is the melting temperature, and a$\left[\frac{F}{T^n L^2}\right]$ is an empirical constant, and n is a positive integer chosen to fit the available data. Next, a force balance requires that the moment be in equilibrium Thus, $r^2\tau$=const. Combining these, we can write,

$$\frac{T - T_m}{T_R - T_m} = \left(\frac{R}{r}\right)^{n/2}, r \geq R$$

FSW joins two pieces at temperatures less than the melting temperature which makes $T_R \leq T_m$. As long as n is positive (a reasonable assumption) this requires that the temperature gradient causes heat to be conducted back towards the tool. There is no reasonable mechanism which allows the tool to be a heat sink of sufficient magnitude for this to occur. The possibility that transients were causing temperature pulses moving through the material was proposed. However, even an oscillatory heat generation pattern at the pin tool surface will still experience the maximum temperature at the tool surface and simply oscillates over time. The other possibility is that heat generation occurs preferentially away from the tool surface in a time dependent manner. The thermal pulse cannot migrate, only decay but the maximum temperature location could move with the position of maximum heat generation.

It can be shown that the heat generation and slip planes must be away from the tool surface and the energy equation would require transient thermal behavior. This behavior would be observed in the experimental data but none is apparent. When this contradiction with the MZ model was discovered, the added effect of strain rate was considered. This mechanism is commonly found in the literature describing constitutive relations in plastic deformation. Examples of these models can be found in Miller (1987), Besseling and van der Giessen (1994), and Gilman (1969). These constitutive models have form the basis for finite element (FE) predictions of plastic deformation such as the MatMod equations developed by Miller (1987).

Start by determining a simplified functional relationship between temperature, strain and strain rate in the range of conditions found in FSW. Data is scarce but in Miller (1987) some data is available. We require that the total moment exerted at any radial position be constant The data in Miller was collected at two strain rates, $\dot{\varepsilon}=.02s^{-1}$ and $\dot{\varepsilon}=2.0s^{-1}$. Although it is reasonable to expect that the effect for much larger strain rates will increase, the effects are close to linear except when crossing boundaries on the map between diffusional flow, creep, and "dislocation glide" regimes where the values change abruptly. We have a relationship between temperature difference, strain rate difference, and the change in radius. We pick the temperature and strain rate difference and calculate the change in radius. The results showed that the trends were correct but that the effect of strain rate was too small to fully account for the observed weld region.
In conclusion, the MZ model appears to have questionable validity

Single Slip Surface Model (S^3):

This model uses the concept weld plug surrounding the pin tool as a rigid body rotating with the tool. In this case, the weld plug rotates as a solid body at the same angular velocity as the tool. There is a single slip plane where all of the work input from the tool is converted to heat in the weld material. The weld plug is uniform in temperature and the heat is conducted only away from the weld plug with a negative temperature gradient outside the plug. This type of plastic strain is insensitive to the strain rate. In order for the tool to move through the weld material, the plug must entrain new material on the front edge of the weld plug, rotate it around to the rear and deposit it. By definition, there is no material convected into the weld plug which means that the plug, once established, has very slow exchange with the weld material. Diffusion is the primary mechanism. Thermal Model:

Temperature measurements taken during the FSW process show a maximum temperature of approximately 380C. Measurements were made using a sacrificial thermocouple which limits it to the undeformed portion of the weld material. For the MZ model, this limitation is important because heat generation through friction is volumetrically distributed through the weld plug. For this model the limitation is unimportant because the heat generation is concentrated at the single slip plane and the weld plug is a uniform temperature with heat removal only by conduction outside the slip plane.

An estimate of the maximum temperature can be made and compared to the measured value. We start with the simplified form of first law of thermodynamics,

$$\dot{W}_{in} = \dot{Q}_{out}.$$

The work in is the work supplied by the tool and the heat out is removed by conduction. In practice these numbers are not quite that simple to supply. The dynamometer measures all forces. However, only those forces involved in dissipative material motion add to the work input. Heat removal will not be simply by conduction to an infinite plate of weld material. At hot locations, radiation and convection will transfer heat directly to the environment and the plate is finite. The work input will be estimated by,

$$\dot{W}_{in} = \int\left(\tau_{ij} V_j\right) \cdot dA$$

F[N] is the force, V[m/s] is the velocity of the material motion, τ_{ij}[Pa] is the stress tensor, A[m^2] is the area, Ω[rad/s] is the angular velocity, and T[N m] is the torque. The dynamometer measurements allow us to estimate several work inputs. Fortunately all are mutually orthogonal and can be used directly. The work input due to torque is approximately 2.11kW, work from tool translation is approximately .008kW, and work from forces into the plane of the material is approximately 2.2kW.

From the energy balance, this work input is converted to heat and must be conducted away. Several estimates were made of the heat transfer and temperature field but only the most realistic estimate will be described here. In Carslaw and Jaeger (1957) several solutions are developed which may approximate the FSW process. The one used here is a moving strip along a semi-infinite medium where the strip generates heat at a finite rate. To use this solution the top and bottom surface of the weld material is assumed to be insulated to approximate the infinite extent in the z direction. The motion is assumed to take place in the -x direction also infinite and the y values of the domain are assumed to extend from 0 to infinity. Thus the finite extent of the weld material will need to be ignored. The solution is written as,

$$T(x,y) = \frac{\kappa Q}{\pi k V} \int_{X-B}^{X+B} \exp[u] K_0 \{ [u^2 + Y^2]^{1/2} \} du$$

X=Vx/2κ, Y=Vy/2κ, B=Vb/2κ

Q is the heat generated per unit depth, k is the thermal conductivity, V is the velocity, κ is the thermal diffusivity, b is the half width of the strip, and K_0 is the modified Bessel function of the second kind of order zero. The integral is evaluated by using a set of four polynomial approximations to I_0 and K_0 which are accurate over the entire real axis (Ambromowitz and Stegun, NBS), and numerically integrating the integral using a simple trapezoidal rule. Numerical purists will disagree on the use of the trapezoidal rule but the function is relatively well behaved if plotted, the accuracy requirements are modest as this is a rough estimate, and a sensitivity study on the number of subdivisions showed that it converged very easily. The resulting profile had a maximum temperature of approximately 400C which agrees reasonably well with measurements. The value for b was set as the weld plug radius. This choice does not reflect the actual heat transfer area (a semi-circle) but does not distort the width of the initial disturbance. The relatively good agreement between predicted temperatures and measured maximum temperature simply indicates that the overall balance between measured power input and the measured temperature appears to be reasonable. It also indicates that the models and assumptions used also appear to be reasonable. It does not represent a real predictive capability.

Mechanical Model:

Theoretical Calculation:

The simplicity of this model makes it possible to calculate the required forces. The assumptions needed to make this calculation are that both the temperature and geometry of the plug are known beforehand. Using the geometry seen in photographs of the weld cross section, the geometry is approximated as a tapered cylinder. The required properties are the yield stress as a function of temperature. In the previous model (MZ), the yield stress was a function of both temperature and strain rate. The assumption was that the mechanisms were creep and diffusion. In this model the single slip plane requires a very high strain rate mechanism which is essentially strain rate independent. The uniform temperature weld plug will be assumed to be at 370C which is approximately the measured value. At this temperature the yield stress for aluminum alloy 2219 is 26MPa. The moment is written as,

$$M = \int dM = \int_{z=0}^{z=.6} \tau 2\pi r^2(z) dz$$

The equation for r as a function of z is linear, or r(z) = a + bz

$$M = 2\pi\tau \int_{z=0}^{z=.6} (a+bz)^2 dz = 109\ \mathrm{N \cdot m}$$

Experimental Calculation:

From the experiments, the measured torque is

$$M_{torque} = 35 ft \cdot lbf = 47 N \cdot m.$$

The contribution from material moved by the threads is added in a complex pattern of material motion which, in a reference plane moving with the tool would appear as a toroidal movement.

$$M_{threads} \cong 50 N \cdot m$$

Combining both contributions, the total moment from experimental measurements is

$$M_{total} = M_{torque+}M_{threads} \cong 98N \cdot m$$

This is within 10% of the calculated value which is better agreement than we should get given the assumptions which were made. Again, this analysis is not a predictive tool because it requires the temperature and weld plug shape known in advance. It does support the validity of the S^3 model by showing that the forces required match the forces supplied (at least to the accuracy available).

Weld Plug Shape Prediction using the S^3 model:

During the FSW process, the actual shape and temperature at the slip surface is not a random event. Instead, these variables are selected on the basis of physical principles which, if determined correctly,
provides a true predictive capability not yet developed. In mechanics, both solid and fluid, a common principle which has been successfully used to model observed phenomena is a minimum energy concept. The FSW process is not static so we modify the concept to be a minimum power requirement. The shape of the weld plug will change to minimize the required power input subject to boundary conditions imposed by the tool shape and motion. The power requirement will strongly depend on the plug temperature which also depends on the power input which dissipates to increase the internal energy. The coupled processes of energy and mechanical power must be satisfied simultaneously to determine either the temperature or the shape of the weld plug. A crude algorithm based on hand calculations was developed which would help determine weld plug shape. Three candidate shapes were evaluated. The first shape simply follows the tool profile (pin and shoulder) which has the minimum weld plug volume. The second shape, called a modified mushroom shape, represents a simplification of the shapes observed in photographs. The final shape is a simple cylinder with a radius of the tool shoulder.

Case 1: Tool shape - total Power Required $\tilde{P}_{tot} = \tilde{P}_T + \tilde{P}_S \cong 2\pi\sigma\Omega\left(7.37x10^{-7}\right)$

Case 2: Modified Mushroom Shape - $\tilde{P} = \sigma\Omega 2\pi\left(8.55x10^{-7}\right)$

Case 3: Cylinder Shape - P $\cong 2\pi\sigma\Omega\left(1.024x10^{-6}\right)$

By comparing the coefficient of all three shapes, the ranking suggests that the cylinder is the least likely. Because the tool shape is extreme, the likely shape of weld plug would be probably lie between the modified mushroom and the tool shape. The calculation should be continued with shapes lying between these two shapes to finally converge on the most likely shape. Although this is tedious to calculate by hand, it may be possible to write a simple computer code which can find the minimum power shape using a search algorithm.

Computer Optimization of Shape:
Start by using an approximate equation for the required power,

$$\tilde{P} = (\sigma\Omega\pi/2)(r_{i+1} + r_i)^2\sqrt{(r_{i+1} + r_i)^2 + (z_{i+1} + z_i)^2}$$

We can minimize this by ignoring the constants (σ, Ω, and π)

$$Min(\tilde{P}) = Min\{(r_{i+1} + r_i)^2\sqrt{(r_{i+1} + r_i)^2 + (z_{i+1} + z_i)^2}\}$$

The computer code used a very simple search algorithm. Like most search algorithms, this one will converge on a local minimum which may or may not be the global minimum. In fact, the actual physical shape of the weld may not be a global minimum or any particular local minimum. However, nature is often kind and the calculated minimum usually corresponds to the most realistic value. If there is doubt, different initial conditions will often find other extrema, should they exist. This algorithm was used to calculate the shape of the weld plug for two conditions. The first is that the bottom is free to move and the second closed the bottom of the weld plug with a radius equal to zero. Both calculated shapes were independent of the initial conditions and were quite similar except for the bottom several points.

Material Motion:

MZ Model:
One of the striking differences between the two models discussed here, (the MZ and S^3 models) is the behavior of the moving material surrounding the pin tool. The area surrounding the pin tool in the MZ model acts as a reservoir which exchanges material freely with its surroundings. If we assume that the material in front of the pin tool is simply

ingested into the mixed zone and that the material in the mixed zone is completely mixed before it exits at the rear, the composition of any solutes of the alloy is easy to predict using a simple rate equation. With these assumptions, the equation is,

$$\frac{C-C_0}{C_0} = -\exp\left(-\frac{4Vt}{\pi d}\right)$$

V is the forward velocity of the tool, C_0 is the concentration of an solute in the weld material at the current position, C is the concentration of the solute in the weld plug, d is the diameter of the weld plug and t is time. As expected, the concentration of any solute relaxes towards the local value in the form of a decaying exponential function. Large velocity in the x direction and small plug diameter reduces the transition time. The effect of diameter may seem surprising at first but it simply represents the ratio of storage volume to the boundary area.

S^3 Model:
With a single slip surface, the weld plug behaves like a solid body rotating with the pin tool. Material is transported around the weld plug in a thin layer. Exchange of material with the surrounding weld material is slow. Of interest is the maximum thickness of the thin layer transporting the transporting material around the weld plug, which occurs at $\theta = \pi$,

$$T_{\max}(\pi) = \frac{2V}{\Omega} \cong 7.6x10^{-5}m.$$

This estimate is useful to evaluate some previous measurements using tracers, in particular Boeing's experiment using small spheres for tracers. Here we see a very thin layer, much thinner than the diameter of the tracer spheres. In theory, tracers should not influence the behavior of the process being studied but these spheres are larger than the predicted width of the layer. This makes detailed conclusions from that experiment suspect. While the tracer spheres were much too large to provide information on the S^3 model is does provide a test of the MZ model. For a process like that of the MZ model there is no thin layer which would be disturbed by these spheres. The spheres should be ingested into the large area of plastically deforming material surrounding the pin tool similar to any solute found in the surrounding material. Like the previous argument concerning the solute concentration for the MZ model, the spheres should be released randomly from the mixed zone in both time and location. The pictures actually show that the spheres were left primarily in a line behind the weld plug. The actual dynamics of the interaction between hard spheres and any type of plastically deforming material is a complex issue. The behavior of a spheres with dimensions larger than a layer of deforming material (S^3)cannot be predicted. Similarly the behavior of hard spheres in a deforming material with continuously variable strain rates (MZ) currently defies prediction. With that caveat, we can argue that it does suggest the material surrounding the pin tool is not a well mixed mass of continuously deforming material such as proposed by the MZ model.

Conclusions:

Given the S^3 and the MZ model and the estimates made above, how can we choose between the two models? One fairly strong test is to run an experiment with the tool going from one material into another. If the materials have detectably different alloys, the composition of the weld plug should not change from the initial material if the S^3 model is correct. The composition of the weld plug should gradually change from the composition of the first material to the composition of the second material if the MZ model is correct. The test ends by removing the tool from the second material, making a cross section of the weld plug, and measuring profiles of solute composition in the cross section of the weld plug. This is planned and may be completed before the end of this phase of the project. A word of caution is that either model will be an idealization of the actual process. There will be some exchange of material even if the S^3 model is the best description. To discriminate between the two models we should consider zero exchange as one extreme S^3, and the composition previously predicted from the MZ model as the other extreme. The actual results should lie somewhere between those two extremes and a clear choice emerges if the results were very near one prediction or the other. The final possibility is that the composition of the weld plug is completely of the second material which would not confirm either of the two models discussed here. In that case another model is needed. Perhaps the one proposed by Boeing where there is no weld plug and the softened material is simply pushed around the tool.

Beyond the question of simply identifying the mechanisms which are important in the FSW process we can use this type of modeling to provide guidance in using this process for different materials and different geometrys. For example, it is now possible to predict the tool forces and operating temperatures for material of a different thickness. We do this by using both the energy balance and the force balance and require that they be in equilibrium. The basic technique was described previously in the report. Similarly, the forces and temperatures for different materials can be predicted using the same techniques with data relating the yield stress to the temperature of that material.

More interestingly we are now able to study some of the details of the process. Photographs of the weld cross section shows a vortex like structure oriented along the weld joint. This structure may or may not have any importance in the weld properties. This rolled up structure appears to be caused by the downward motion of material caused by the rotation of the threads. Recent data and the opinion of the people studying this process indicates that the z forces on the tool are caused by this motion and that it represents important work input into the weld. The models support this argument by requiring that the z forces and predicted material motion due to the thread rotation are needed to maintain the balance between the thermal outputs and the mechanical inputs. If the primary importance of the motion of the threads is simply to increase the work input, we can eliminate the threads and add additional mechanical energy in other ways such as by increasing the diameter of the weld plug (tool shoulder diameter) or by increasing the tool rotational speed of the tool or both and measure the weld properties with and without the vortex structures.

Some potential optimizations of the process can be identified using the model. Tool forces can be reduced by increasing the weld temperature. The temperature can be increased by increasing the mechanical work input or reducing the translational (x) speed of the tool. Mechanical work input comes primarily from either the rotation of the tool and the motion caused by the pin tool threads (z forces). The translation of the tool (x forces) represents a very small input of mechanical energy. Of the important inputs, the z forces are the most difficult to support during the welding process which again argues that the rotational work input is the easiest to increase. An increase in the rotational speed should then be accompanied by an increase in thread pitch to alter the relative effects of rotation with z forces.

If weld temperatures strongly influence the resulting tensile strength of the weld, it is possible to increase translational speed and maintain weld strength by adjusting the work input (probably the rotational work input alone) to maintain a constant weld temperature. Similarly, if the weld temperature is not (by itself) an important factor in weld strength, mechanical work input can be increased at constant translational speed to reduce the needed tool forces.

The last comment is that the tool shoulder currently has two purposes. The first is to add rotational energy and the second is to prevent the material from deforming plastically in the z direction. Potentially some of the disadvantages of operating at higher temperatures (the tendency to soften the material to such an extent that it is not effectively constrained by the tool shoulder) could be eliminated by adding an annular extension of the shoulder that does not rotate or add mechanical work. The relative size of the rotating portion of the shoulder relative to the size of the non-rotating portion could be changed to improve weld characteristics. Possibly the entire shoulder should be stationary.

As we can see, the result of modeling is to add more questions than it answers and the primary objective is not to understand FSW but to help direct the research to improve it.

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