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A conceptual model for the process variables related to heat generation in friction stir welding of aluminum

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Abstract—This paper seeks to describe relationships between the independent process variables and the dependent process outcomes related to heat generation and dissipation in friction stir welding. A conceptual model, proposed earlier, has been modified to specifically distinguish between plastic work and friction in the generation of heat. A case study is used to confirm and explore the relationships expressed in the conceptual model. Further, a method for expressing friction coefficient variation with respect to the key process variables is introduced.

Keywords: Friction stir welding; Aluminum; Plastic deformation; Modeling; Friction

It is important for users of friction stir welding (FSW) to have a conceptual understanding of how the process works. Such an understanding is helpful in deciding how to change process conditions to achieve desired effects, such as for improving joint strength, for eliminating certain common weld defects, and for transferring a known welding procedure to new conditions. Computer-based models and empirical studies of the stir welding process have been developed by many researchers to examine heat transfer, metallurgical evolution and material flow. This work has been very useful for building an understanding of the different physical effects in FSW. A general examination of the relationships between variables can now be used to develop a conceptual model of the process. The goal of this paper is to propose a conceptual model that relates the different process variables with key process conditions in a way that will allow the practitioner of FSW to develop a general understanding of the process. In addition, the framework for coefficient of friction during the friction stir process is discussed.

A conceptual model is proposed that relates the main process variables, structured around the interrelation of the main categories of physical effects that come into play in the generation and distribution of heat in FSW. A preliminary version of this model was published earlier [1], but the original formulation has been modified here to specifically distinguish the effects of friction and plastic work on the generation of heat, which is an important distinction. The physical effects included in the model include metallurgical effects, mechanical effects, heat generation effects and heat transfer effects. These physical effects can be expanded to show each of the process variables and how they interact, as shown in Figure 1. In this diagram the process variables are represented in boxes with solid borders, while the physical effects are represented in boxes with dashed borders. The arrows start at a process variable, pass through a physical effect, then terminate with a process variable.

First, the flow stress of the workpiece at the welding tool surface is the result of the thermal history, the amount of strain and the strain rate experienced by the workpiece. Similarly, the friction force is affected by the workpiece material and the thermal history it experiences as it approaches the tool. Thermal history effects can further be subdivided into slow processes that depend on the temperature distribution in advance of the welding tool, which result in metallurgical alteration of the workpiece, and rapid, deformation heating that takes place as the material is deformed by the pin. The relatively slow metallurgical alteration of the workpiece can be thought of as preconditioning that the workpiece

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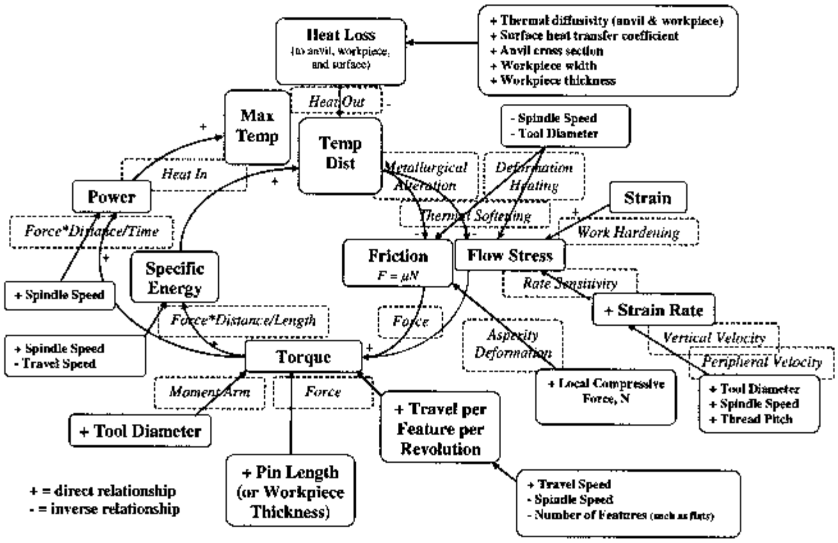

Figure 1. Relationships between variables with physical effects overlaid.

experiences as it heats from room temperature to the temperature just in front of the pin. This preconditioning has the effect of eliminating the effects of thermomechanical treatments in the base metal, so that alloys of identical composition behave essentially the same in welding. Softening from deformation heating occurs from plastic work and friction caused at the surface of the welding tool pin.

Friction between surfaces has been extensively studied in the past and it has been shown that friction is strongly dependent on local conditions. For sliding friction between clean metallic surfaces at high temperatures, the friction coefficient has been shown generally to decrease with increasing temperature [2]. No detailed study of the variation of friction coefficient at the temperatures and relative velocities commonly experienced in FSW has been carried out, but for the purpose of a conceptual model, only the general trend is required (some preliminary data on the coefficient of friction is presented later in this paper). It should also be noted that the effect of the friction coefficient, μ, has been placed in the box for friction force simply as a means of conserving space in the model layout. Strictly speaking, the friction coefficient should be a separate box just above friction force, and should be related to friction force through the equation $F = \mu N$. Some preliminary evaluation of the friction coefficient during FSW is given below. Deciphering the friction coefficient is critical for modeling efforts.

Continuing in Figure 1, flow stress and friction force lead to the development of spindle torque as the workpiece material resists tool rotation. When torque is applied through rotation at a given speed, heat is generated in the workpiece. The torque can be used to calculate the power (energy per unit time) delivered to the workpiece simply by multiplying the torque by the spindle speed, and can be used to calculate the specific energy (energy per unit weld length) by dividing the power by the travel speed. In this model the specific energy is related to the temperature distribution within the workpiece, as justified earlier [1]. The variation in maximum workpiece temperature near the welding tool with respect to welding speed is better represented by the weld power in experimental results. The welding speed certainly has an effect on the maximum temperature, but this effect influences the maximum temperature through change in the torque that accompanies the change in welding speed.

Returning to Figure 1, the temperature distribution is the result of the balance between heat generation and heat loss to the environment. Important variables in the determination of the temperature distribution are the thermal diffusivity of the workpiece and anvil (how easily the heat dissipates), the size of the workpiece and anvil, and the workpiece surface convection characteristics. The maximum temperature is not linked to the flow stress in Figure 1, since this effect is already captured in the deformation heating effect, discussed above.

Comment should be made here about the dual nature of heat generation in FSW. Heat is generated in FSW both by friction and by plastic work, depending on whether there is local relative motion between the tool and the workpiece, generating frictional drag at the interface, or whether there is local seizure. Local seizure can be the result of certain reentrant features cut into the surface of the tool, such as flats or grooves, or can be caused by certain complex tool motions that are not based on pure rotation [3–5]. These two heat generation mechanisms may coexist at any given time in different regions of the tool. While it is impossible to experimentally isolate the proportion of heat generation attributable to each of these mechanisms, both mechanisms have been experimentally observed [6] and numerical model results attribute heat generation to both mechanisms being simultaneously present [7].

Conceptual modeling of the relationships between the variables can be further enhanced by showing whether the relationship is a direct relationship or an inverse relationship, as shown in Figure 1. In this diagram the relationship is coded as a '+' sign for a direct relationship and a '−' sign for an inverse relationship. As will be seen in the case study below, the relationships between variables can be used to help understand how changing welding conditions will influence the key features of flow stress and friction, torque, heat generation and workpiece temperature.

In this case study, an experiment was performed to explore the effect of spindle speed on welding conditions. A fixed-geometry bobbin tool was used to weld 11.9 mm 2195 Al–Li alloy plate. The fixed-geometry, bobbin-style FSW tool is a variation of FSW that employs two shoulders connected by a pin, as shown in Figure 2 [8,9]. The welding tool design features and welding speed are defined in Table 1. In each weld the forces against the welding tool were recorded and plotted as a function of spindle speed, as shown in Figure 3. All welds produced were free of volumetric defects. The resultant in-plane force was observed to initially decrease, reach a minimum value, and then increase with increasing spindle speed. At the same time, the spindle torque was observed to continuously decrease, while the weld

Figure 2. Bobbin-style FSW tool, workpiece cut away for clarity.

Table 1. Tool design for welds in 11.9 mm 2195

Effective shoulder diameter, mm (in)	25.4 (0.999)
Scroll depth, mm (in)	1.3 (0.05)
Scroll pitch, mm (in)	3.3 (0.13)
Scroll width, mm (in)	2.5 (0.10)
Pin diameter, mm (in)	12.7 (0.500)
Thread pitch, mm (in)	1.58 (0.063)
Number of features (flats)	4
Welding speed, mm min^{-1} (in min^{-1})	203 (8.0)

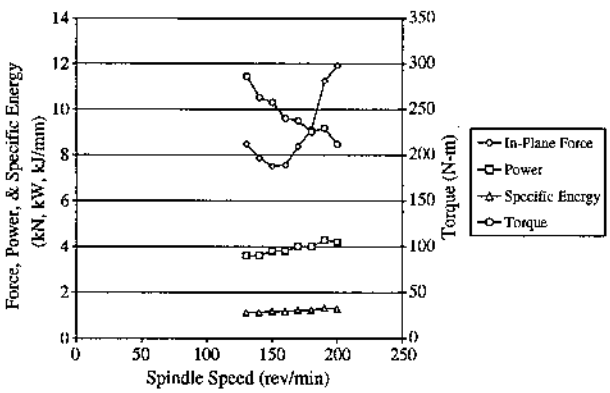

Figure 3. Torque, in-plane force, weld power and specific energy as a function of spindle speed for FSW of 11.9 mm 2195 Al–Li plate.

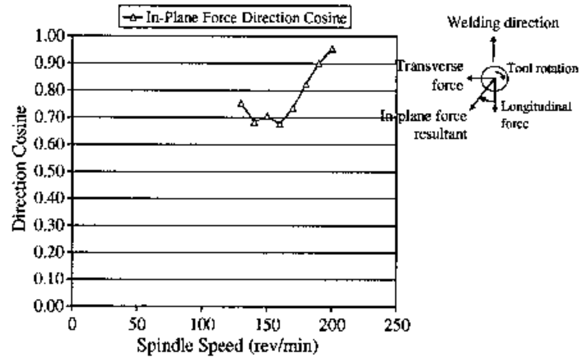

Figure 4. In-plane force direction cosine with respect to spindle speed.

power and specific energy increased. The direction cosine of the in-plane force is plotted as a function of spindle speed in Figure 4. As the spindle speed increases, the in-plane force becomes more aligned with the welding direction. These observations can be examined within the context of the conceptual model, shown in Figure 5. In this figure, upward influence is indicated by a heavy dark line, downward influence is shown as a heavy gray line, and neutral influence is shown as a dotted line.

1. It was observed in Figure 3 that increasing the spindle speed resulted in decreased torque, which, according to the conceptual model, would exert a downward influence on the power and specific energy.
2. As shown in Figure 5, the increase in spindle speed also exerts an upward influence on the power and specific energy. It was observed in Figure 3 that the power and specific energy actually increased with increasing spindle speed, in spite of the decreasing torque. Since no change was made to the heat loss characteristics, the increasing power and specific energy would be expected to increase the maximum temperature and the temperature distribution, although these were not measured in the present study.
3. The model predicts that the increasing temperature distribution increases metallurgical alteration in advance of the welding tool, exerting a downward influence on the flow stress and the friction force.
4. Increasing the spindle speed also has the effect of increasing thermal softening by deformation heating, exerting an additional downward influence on the friction force and flow stress at the tool. The effect on flow stress is counteracted, to some unknown extent, by the presumed increase in strain rate. However, it has been shown that the torque continues to decrease with increasing spindle speed, even beyond the point at which no additional far-field temperature distribution increase is expected, and the deformation heating effect is stronger than the effect of increasing strain rate, resulting in a continued decrease in flow stress with increasing spindle speed [1].
5. The model shows a positive relationship between local compressive force and the friction force. It was observed that as the spindle speed increased, the net in-plane force also increased and the direction of the in-plane force became more aligned with the welding direction, exerting an upward influence on

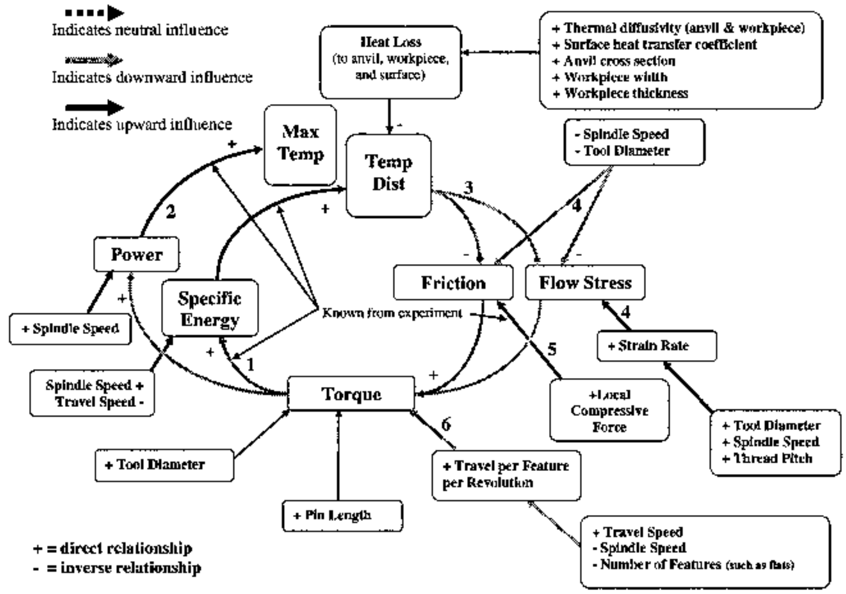

Figure 5. Influence between variables for increasing spindle speed.

the friction force that competes with the negative influence of the increased metallurgical alteration and deformation heating. The local compressive force also includes the effect of the plunge force, but in a fixed-gap bobbin tool this force is internal to the tool and could not be measured.

6. The decreasing flow stress and friction force would be expected to reduce the torque, as was observed. The model also predicts the downward influence of the decreasing travel per feature per revolution, although it is impossible to isolate the effect in the data collected in the present experiment. However, a previous discussion of this conceptual model [1] showed that if the effect of travel per feature per revolution is isolated, increasing spindle speed still results in decreasing torque.

It is speculated that the increasing in-plane force with respect to spindle speed is the direct result of the decreasing friction coefficient predicted by the model. In the bobbin-welding experiment, as the spindle speed increased, the in-plane force became almost entirely composed of force required to push the tool in the welding direction, which implies high compressive force between the leading edge of the welding tool pin and the workpiece. It is conceivable that the increasing in-plane force provides a mechanism for regulating the production of heat as the spindle speed increases, thus perpetuating the welding process. It is notable that in the present experiment, the power and specific energy continue to increase with increasing spindle speed, instead of staying constant. This is an area where additional fundamental research into the mechanics of the process is needed.

It is interesting that at low spindle speed the in-plane force was observed to decrease with increasing spindle speed, as shown in Figure 3. It seems logical that at a spindle speed of zero, all material transfer around the pin would be due to extrusion and the in-plane force would be very high. It can be supposed that as the spindle speed increases it begins to assist in material transfer and to produce thermal softening, causing the in-plane force to decrease. Eventually, a minimum force condition is reached where further increase in the spindle speed causes the in-plane force to increase due to the reduced friction coefficient, as discussed above. Perhaps the minimum in-plane force point offers a convenient indicator of optimum spindle speed for a given travel speed, since this point minimizes the force on the tool. Higher spindle speeds only serve to increase heat input and in-plane force.

For modeling of heat input and material flow, a critical input required is the coefficient of friction during the friction stir process. To date, a framework for coefficient of friction during the friction stir process has not been adequately developed. The metalworking literature primarily relies on either the Coulomb friction model ($\tau = \mu\sigma_n$, where the shear stress τ is proportional to the normal stress σ_n with a proportionality constant μ, the coefficient of friction) or the constant shear model ($\tau = m\sigma_y$, where the shear stress τ is proportional to the material yield stress σ_y with a proportionality constant, m) [10]. The value for μ during metalworking operations is generally <1, but values >1 have been reported for machining of metals. On the other hand, the value of m is 0 for the slipping condition and 1 for the sticking condition. Various models of FSW have used these frameworks, although they had to assume the value of the coefficient of friction [11–14]. Typically, a value in the range of 0.3–0.4 for μ has been assumed in heat generation models [11–13]. Kalya et al. [15] correlated torque, process specific energy and temperature for the friction stir process. The modeled torque (M) can be expressed as $M = A\omega^a v^b$, where ω is the spindle rotation rate, v is the traverse rate, and A, a and b are data correlation constants. Figure 6 shows the variation of coefficient of friction with modeled torque for two aluminum alloys. The values for the coefficient of friction range from 0.35 to 1.3 for these alloys. This data

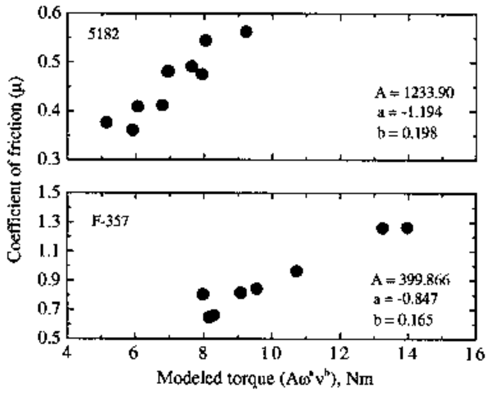

Figure 6. The variation of coefficient of friction with modeled torque for two aluminum alloys.

and the procedure for repeating the results with other alloys will be described in a future publication [16]. In brief, these values were computed using a relationship, $\mu = (3M_e/2F_zR)$, where M_e is the measured spindle torque, F_z is the measured normal force and R is the shoulder radius of the tool. The magnitude of the coefficient of friction is similar to those observed for rolling and metal cutting. In many ways the shearing of the layer in front of the pin, the compression of material on the retreating side of the pin, and the interaction between the tool and workpiece are similar to the rolling and metal cutting processes.

As emphasized above, the temperature generation, material flow strength and coefficient of friction are all intertwined. The modeling and simulation efforts can use experimentally obtained empirical relations to obtain more realistic information.

In spite of the apparent simplicity of the FSW process, there are still many aspects of the process that remain unexplained. This study proposes a conceptual model of the mechanisms of heat generation in FSW for the purpose of facilitating a general understanding of the process. However, in describing the process, several questions emerge. For example, an adequate description of the mechanics of frictional heat generation under the conditions of FSW does not exist. In addition, quantitative study of the effects of different variables could lead to assigning weighting factors to the interactions between variables. This work could, for example, yield valuable insight into the relative magnitude of the role of friction vs. plastic work in heat generation and the relative importance of strain rate effects.

References

[1] K.J. Colligan, in: R.S. Mishra, M.W. Mahoney, T.J. Lienert, K.V. Jata (Eds.), Friction Stir Welding and Processing IV, TMS, Orlando, FL, 2007, p. 39.
[2] F.P. Bowden, T.P. Hughes, Proc. R. Soc. London, Ser. A 172 (1939) 263.
[3] W.M. Thomas, D.G. Staines, I.M. Norris, R. de Frias, Friction stir welding-tools and developments, FSW Seminar, Instituto de Soldadura e Qualidade, Porto, Portugal, 2002.
[4] C.J. Dawes, W.M. Thomas, in: Proc. 1st Int. Symp. Frict. Stir Weld., Thousand Oaks, CA, 1999.
[5] P.A. Colegrove, P.L. Threadgill, Development of the Trivex Friction Stir Welding Tool, The Welding Institute, Published on the Internet, 20 February 2003.
[6] K.J. Colligan, S.K. Chopra, in: Proc. 5th Int. Symp. Frict. Stir Weld., Metz, 2004.
[7] P.A. Colegrove, H.R. Shercliff, P.L. Threadgill, in: Proc 4th Int. Symp. Frict. Stir Weld., Park city, UT, 2003.
[8] K.J. Colligan, US Patent 6,669,075, December 2003.
[9] K.J. Colligan, J.R. Pickens, in: K.V. Jata, T.J. Lienert, M.W. Mahoney, R.S. Mishra (Eds.), Friction Stir Welding and Processing III, TMS, 2005, p. 161.
[10] B. Avitzur, Friction, Lubrication and Wear Technology, ASM Handbook, vol. 18, p. 59.
[11] O. Frigaard, O. Grong, O.T. Midling, Metall. Mater. Trans. A 32 (2001) 1189.
[12] M.Z.H. Khandkar, J.A. Khan, A.P. Reynolds, Sci. Technol. Weld. Joining 8 (2003) 166.
[13] H. Schmidt, J. Hattel, Modell. Simul. Mater. Sci. Eng. 13 (2005) 77.
[14] H.R. Shercliff, P.A. Colegrove, in: R.S. Mishra, M.W. Mahoney (Eds.), Friction Stir Welding and Processing, ASM, 2007, p. 187.
[15] P. Kalya, K. Krishnamurthy, R.S. Mishra, J.A. Baumann, in: R.S. Mishra, M.W. Mahoney, T.J. Lienert, K.V. Jata (Eds.), Friction Stir Welding and Processing IV, TMS, Orlando, FL, 2007, p. 113.
[16] P. Kalya, M. Yadava, R.S. Mishra, in preparation.