Dimensionless correlation to estimate peak temperature during friction stir welding

G. G. Roy, R. Nandan and T. DebRoy*

A dimensionless correlation has been developed based on Buckingham's π-theorem to estimate the peak temperature during friction stir welding (FSW). A relationship is proposed between dimensionless peak temperature and dimensionless heat input. Apart from the estimation of peak temperature, it can also be used for the selection of welding conditions to prevent melting of the workpiece during FSW. The correlation includes thermal properties of the material and the tool, the area of the tool shoulder and the rotational and translation speeds of the tool. The peak temperatures reported in the literature during FSW of various materials and welding conditions were found to be in fair agreement with the proposed correlation.

Keywords: Friction stir welding, Dimensional analysis, Peak temperature, Buckingham's pi theorem

Introduction

Friction stir welding (FSW) is a solid state welding process where a rotating tool with a large diameter shoulder and a much smaller cylindrical threaded pin passes through the interface of the two plates to be joined.[1] Heat is generated by friction between the tool and the workpiece as well as by plastic deformation of the alloy. The rotational and translational speeds of the tool, the tool design and the properties of the workpiece and the tool affect the temperature and plastic flow fields. The peak temperature and the temperature field in FSW have been widely studied both experimentally and theoretically because they affect both the welding process as well as the welded alloys significantly. However, currently there is no simple method to estimate the peak temperature during FSW without comprehensive numerical modelling of heat transfer and plastic flow.

Most of the initial quantitative studies of temperature fields and peak temperature were based on heat conduction theory.[2–6] These models ignored important physical processes such as the plastic flow of the workpiece material near the tool and had been replaced by more accurate and computationally more intensive process models. Seidel and Reynolds[7] developed a model to study the effect of weld pitch on the material flow. Colegrove and Shercliff[8,9] used a material flow model and found that different tool designs did not result in any significant changes in heat generation. Ulysse[10] modelled FSW of thick aluminium plates, based on a three-dimensional viscoplastic model. Two-dimensional steady state heat transfer and fluid flow for FSW of 304 steel was modelled by Cho *et al.*[11] Most recently, Nandan *et al.* reported fully coupled model of three-dimensional material flow and heat transfer during FSW of aluminium alloy,[12] 304 stainless steel[13] and 1018 C–Mn steel.[14] They considered spatially variable heat generation rates, non-Newtonian viscosity as a function of local strain rate and temperature, temperature dependent thermal conductivity, specific heat and yield stress. The computed temperature fields and TMAZ agreed well with the corresponding independent experimental data. Although the comprehensive three-dimensional models have been developed to describe the temperatures and material flow during FSW, they are computationally very intensive because they involve solution of complex three-dimensional equations of conservation of mass, momentum and energy. Here the authors present a dimensionless correlation that may be used to estimate peak temperature for a wide range of welding parameters and different tool workpiece combinations without any time consuming and expensive comprehensive numerical modelling.

Dimensional analysis

Buckingham's π-theorem is used to develop a dimensionless correlation for the calculation of peak temperature during FSW of different engineering alloys. First, the variables that influence the peak temperature T_P are identified. They are:

(i) the heat input per unit length to the workpiece $f\,\sigma_8 A$
(ii) the rotational velocity of the tool ω
(iii) the thermal property of the workpiece k/C_P
(iv) the translation velocity of the tool U and
(v) the initial or preheat temperature of the workpiece T_{in}

In these variables, σ_8 represents the yield stress of the workpiece at a temperature of $0{\cdot}8T_S$ where T_S is the solidus temperature, A is the cross-section area of the tool shoulder defined as

$$A=\pi\left(R_o^2-R_i^2\right)$$

where R_o and R_i are the shoulder and pin radius

Pennsylvania State University, University Park, PA, USA

*Corresponding author, email debroy@psu.edu

Published by Maney on behalf of the Institute
Received 20 April 2006; accepted 27 April 2006
DOI 10.1179/174329306X122811

respectively. The factor '*f*' represents the ratio in which heat generated at the tool shoulder/workpiece interface is transported between the tool and the workpiece. Its value can be calculated based on steady-state one dimensional heat transfer from point heat source located at the interface of dissimilar materials[15]

$$f=\left[(k\rho C_P)_W\right]^{1/2}\Big/\left[(k\rho C_P)_T\right]^{1/2} \quad (1)$$

where the subscripts W and T indicate the workpiece and tool respectively, k is the thermal conductivity, C_P is the specific heat and ρ is the density of the material. Applicability of equation (1) has been established by Lienert *et al.*[16] based on experiments. The value for '*f*' for FSW of aluminium alloy with steel tool is found to be >90%, while it is only 60% for FSW of 1018 C–Mn steel with tungsten tool and 40% for 304 stainless steel with tungsten tool.[12–14]

During the FSW process, heat is generated by both friction at the shoulder/workpiece interface and plastic deformation of the workpiece.[2] Since the coefficient of friction changes with temperature and its values at different temperatures are scarce, frictional heat generation is difficult to calculate accurately. Therefore, the heat generation rate is often calculated from the yield stress. Since the yield stress depends on temperature, its value at $0{\cdot}8T_S$ is assumed for simplicity to estimate the maximum shear stress for plastic deformation at the surface.[12–14] Since in many FSW systems, >80% of the heat is generated at the shoulder/workpiece interface,[12–14] the heat generation at the surface of the pin is neglected. The initial or preheat temperature T_{in} is important because a given heat input will yield higher peak temperatures for higher initial temperatures. The thermal property of the material k/C_P is an important parameter because it affects heat transfer and peak temperature. Since thermal properties k and C_P are temperature dependent, their values have been calculated at the mean temperature T_M by

$$T_M=0{\cdot}5^*(T_S+T_{in})$$

Table 1 shows all six pertinent variables including peak temperature for dimensional analysis with their dimensions in $MLT\theta$ system, where M, L, T, θ represent mass, length, time and temperature. The total non-dimensional numbers according to Buckingham π-theorem will be (6–4)=2; one for peak temperature and the other for heat input into the workpiece.

The non-dimensional peak temperature is obtained as

$$T^*=T_P/T_{in}$$

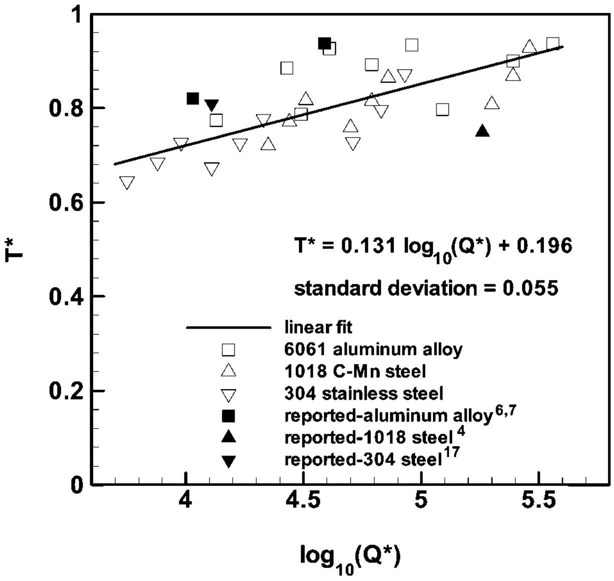
or more appropriately in terms of temperature ranges, as follows

$$T^*=(T_P-T_{in})/(T_S-T_{in}) \quad (2)$$

where T_S has not been treated as separate variable because its effect has already been embodied in the variable σ_8.

The non-dimensional heat input is obtained as

$$Q^*=(f\sigma_8 A\omega C_P)/\left(kU^2\right) \quad (3)$$



1 Linear relationship between dimensionless temperature and log of dimensionless heat input to workpiece

Results

Figure 1 shows a plot of dimensionless temperature versus dimensionless heat input. Data for peak temperatures at different rotational speeds, translational velocities, tool geometries and for three different materials, namely 6061 aluminium alloy,[12] 1018 C–Mn steel[14] and 304L austenitic stainless steel[13] have been obtained from a comprehensive three-dimensional mathematical model of FSW process. These peak temperatures in dimensionless form have been plotted against the dimensionless heat input. Some of the reported experimental data, depicted by filled symbols, are also superimposed and those are found to be in good agreement with the developed correlation. As can be seen from the figure, the data can be fitted with in the following relation with a standard deviation of 0·055

$$T^*=0{\cdot}131\ln(Q^*)+0{\cdot}196 \quad (4)$$

The above relation is valid for values of Q^* between 5×10^3 and 5×10^5. This range of Q^* is typical for the operation of the FSW systems reported in the literature. Unlike the values of T^*, the values of Q^* vary by two orders of magnitude. As a result, it is convenient to correlate T^* as a function of log(Q^*). The above relation may be used to estimate the peak temperature

Table 1 Pertinent variables for dimensional analysis with their dimensions in *MLTθ* system

Variable	Dimension
Peak temperature T_P	θ
Heat input per unit length that transmit towards the workpiece $f\sigma_8 A$	ML/T^2
Thermal property k/C_P	M/LT
Angular velocity of the tool ω	$1/T$
Translational velocity of the tool U	L/T
Initial temperature T_{in}	θ

reasonably well during FSW process for a given material tool combination, tool geometry and welding and rotational speeds without any comprehensive modelling.

References

1. W. M. Thomas, E. D. Nicholas, J. C. Needham, M. G. Church, P. Templesmith and C. Dawes: International Patent Application No. PCT/GB92/02203 and GB Patent Application No. 9125978·9, 1991.
2. H. Schmidt, J. Hattel and J. Wert: *Model. Simul. Mater. Sci. Eng.*, 2004, **12**, 143–157.
3. Y. J. Chao, X. Qi and W. Tang: *Trans. ASME*, 2003, **125**, 138–145.
4. X. K. Zhu and Y. J. Chao: *J. Mater. Process. Technol.*, 2004, **146**, 263–272.
5. M. Song and R. Kovacevic: *Proc. Inst. Mech. Eng. B*, 2004, **218B**, 17–33.
6. M. Z. H. Khandkar, J. A. Khan and A. P. Reynolds: *Sci. Technol. Weld. Join.*, 2003, **8**, (3), 165–174.
7. T. U. Seidel and A. P. Reynolds: *Sci. Technol. Weld. Join.*, 2003, **8**, 175–183.
8. P. A. Colegrove and H. R. Shercliff: *Sci. Technol. Weld. Join.*, 2004, **9**, (4), 345–351.
9. P. A. Colegrove and H. R. Shercliff: *Sci. Technol. Weld. Join*., 2004, **9**, (4), 352–361.
10. P. Ulysse: *Int. J. Mach. Tool. Manuf.*, 2002, **42**, 1549–1557.
11. J. H. Cho, D. E. Boyce and P. R. Dawson: *Mater. Sci. Eng. A*, 2005, **398A**, 146–163.
12. R. Nandan, G. G. Roy and T. DebRoy: *Metall. Mater. Trans. A*, 2006, **37A**, 1247–1259.
13. R. Nandan, G. G. Roy, T. Lienert and T. DebRoy: *Sci. Technol. Weld. Join.*, 2006, **11**, (5), 526–537.
14. R. Nandan, G. G. Roy, T. Lienert and T. DebRoy: in press.
15. H. S. Carslaw and J. C. Jaeger: 'Conduction of heat in solids', 2nd edn, 87–89; 1959, Oxford, Clarendon Press.
16. T. J. Lienert, W. L. Stellwag, Jr., B. B. Grimmett and R. W. Warke: *Weld. J.*, 2003, **82**, (2), 1s–9s.