Available online at www.sciencedirect.com
ScienceDirect
Scripta Materialia 94 (2015) 36–39
Scripta MATERIALIA
www.elsevier.com/locate/scriptamat

Cooling rates and peak temperatures during friction stir welding of a high-carbon steel

V. Manvatkar,[a] A. De,[a] L.-E. Svensson[b] and T. DebRoy[a,*]

[a]*The Pennsylvania State University, University Park, PA, USA*
[b]*Production Technology Center, University West, Trollhattan, Sweden*

Received 22 July 2014; revised 29 August 2014; accepted 1 September 2014
Available online 26 September 2014

Friction stir welding can potentially avoid the need for post weld heat treatment for the welding of high-carbon steels. Although control of both peak temperature and cooling rate has been suggested to achieve this goal, the current literature does not provide any help with selecting appropriate welding variables. In order to address this problem, here we present a set of easy-to-use maps of both the cooling rates and the peak temperatures for various welding conditions during friction stir welding of a high-carbon steel.

Keywords: High-carbon steel; Friction stir welding; Cooling rates; Peak temperatures

The welding of high-carbon steels by fusion welding often results in the degradation of ductility and requires subsequent heat treatment to mitigate the harmful effects of martensite formation. A possible recourse is to weld these steels by friction stir welding (FSW). FSW has been used for the welding of various types of steels including the high-carbon varieties [1–12]. Friction stir welded joints of an interstitial-free steel are characterized by finer microstructure and higher strength compared to joints produced by gas tungsten arc welding [8]. The yield strength of joints produced by friction stir welding of a 0.11 wt.% C carbon steel, ST37, with an austenitic stainless steel, SS304, were higher than both the base alloys. The higher strength was attributed to a fine microstructure comprised of pearlite and ferrite [9]. However, the ultimate tensile strength of the joint was higher than that of ST37 steel but lower than that of SS304 steel [9]. Chung et al. [4,10] and Cui et al. [11] examined the feasibility of welding high-carbon steels by FSW. Cui et al. [11] observed martensite in the microstructure of the weld zone during FSW of a 0.72 wt.% C carbon steel and suggested ways to avoid its formation. They proposed selection of appropriate welding variables to maintain the peak temperature below the A_1 temperature or a cooling rate lower than the critical cooling rate for the formation of martensite [11]. Chung et al. [4] avoided martensite formation during FSW of a 0.85 wt.% C carbon steel by maintaining the stir zone temperature below the A_1 temperature of the alloy. However, the current literature does not provide any guidance on selecting welding variables to prevent loss of ductility. Reliable maps of cooling rates and peak temperatures for various welding variables are needed, but are not currently available.

Experimental measurements of a large number of peak temperatures and cooling rates during FSW of high-strength steels are time consuming and expensive. A practical recourse is to use a set of experimental data to adequately test and validate a comprehensive phenomenological model of heat transfer and material flow and subsequently use the model to calculate the necessary cooling rates and peak temperatures. Aeronautical, mechanical, civil and other engineers now routinely use numerical heat transfer and material flow models in critical designs.

Comprehensive numerical heat transfer and material flow models of friction stir welding have been developed and tested by several groups of researchers [13–20]. These models involve solving the equations of conservation of energy, mass and momentum for steady-state conditions considering incompressible viscous flow. Spatially variable local values of heat generation rates and viscosity of the plasticized material are calculated using appropriate sub-models [14–16]. These models have correctly predicted the experimentally measured peak temperature and thermal cycles [13–19], traverse force [20–22] and torque [18–22] in FSW of aluminum alloys [18,20–23], steels [15,16] and a titanium alloy [17,20]. Since the models and their applications are described in detail in the literature, they are not repeated here. Instead a model is validated for the FSW of a high-carbon steel and subsequently used to understand the roles of important welding parameters on the peak temperatures,

* Corresponding author; e-mail: rtd1@psu.edu

http://dx.doi.org/10.1016/j.scriptamat.2014.09.012
1359-6462/

cooling rates and microstructures of the stir zone of a high-carbon steel.

The numerical model is first validated by comparing the computed thermal cycles with the corresponding experimentally measured thermal cycles during FSW of a high-carbon steel at two different tool rotational speeds [11]. Subsequently, the numerically computed peak temperatures and cooling rates are presented as functions of welding speed and the rate of heat input in the form of easy-to-use contour maps. The estimated values of the rate of heat input as function of tool shoulder diameter and rotational speed are also plotted to determine their influence on the peak temperature and cooling rate. The computed peak temperatures and cooling rates are also used to understand the stir zone microstructure of a high-carbon steel for different welding conditions. This is the first paper to provide a practical means to estimate peak temperatures and cooling rates for various welding parameters.

Tables 1 and 2 indicate the temperature-dependent material properties of the 0.72 wt.% C carbon steel [24] and the welding conditions [11] used in the calculations. Figure 1 shows a comparison of the computed and the corresponding measured [11] thermal cycles during FSW of this steel for two different tool rotational speeds at a constant welding speed. The thermal cycles were monitored at the bottom surface of the workpiece below the tip of the tool pin. The computed peak temperatures in Figure 1 are 907 and 1230 K for tool rotational speeds of 200 and 800 rpm, respectively, which agree well with the corresponding experimentally determined values. The good agreement between the numerically computed and the corresponding experimentally measured thermal cycles shows that the model can be used to calculate the peak temperatures and cooling rates during FSW of the 0.72 wt.% C carbon steel.

The peak temperature and cooling rates are examined as function of the rate of heat generation, Q, which can be analytically calculated using the expression suggested by Schmidt et al. [25]:

$$Q = \frac{2}{3}\pi[\delta\tau + (1-\delta)\mu P] \times \omega[(R_S^3 - R_P^3)(1 + \tan\alpha) + R_P^3 + 3R_P^2 H_P], \quad (1)$$

where δ is related to the slip between the shoulder and the workpiece material, τ is the shear yield strength of workpiece material, μ is the friction coefficient, P is the axial pressure, ω is the angular speed, R_S is the shoulder diameter, α is the shoulder cone angle, and Rp and H_P are the pin radius and length, respectively. The values of δ and μ were taken as 0.31 and 0.49, respectively [15,16]. These values are based on previous research [15,16]. However, the effects of variations of δ and μ on the computed peak temperature and cooling rate were examined for a 1.6 mm thick 0.72 wt.% C carbon steel. It was found that when δ was varied between 0.27–0.34 and μ was varied between 0.44–0.53, the computed peak temperatures were in the range of 1146–1156 K and the cooling rates varied between 72–77 K s^{-1} at a tool rotational speed of 500 rpm and welding speed of 6.667 mm s^{-1}. These results indicate that the effects of variation of μ and δ on the computed peak temperatures and cooling rates are small. Figure 2 shows a map of the calculated rate of heat generation as function of tool rotational speed and shoulder diameter. For example, the rate of heat generation changes from 0.95 to 8.0 kW for tool rotational speeds of 100–800 rpm, respectively, for the experimental conditions of Cui et al. [11]. The heat generation rate increases with increase in both the tool shoulder diameter and the tool rotational speed as expected.

Figure 3a,b shows the computed peak temperature at the top and bottom regions of the stir zone as function of welding speed and the rate of heat generation in a 1.6 mm thick steel plate containing 0.72 wt.% C. The results show that the peak temperature increases with an increase in the heat generation rate. This plot can also be used to understand the effect of welding speed. At faster welding speeds, the peak temperature decreases because of lower heat input per unit length. For a given rate of heat input, the difference in peak temperature between the top and bottom of the stir zone increases with increase in the welding speed. Figure 3 also shows that the peak temperature in the stir zone remains below A_1 temperature (996 K) of the 0.72 wt.% C carbon steel at lower rate of heat generation, i.e. at tool rotational speed of 100 rpm or lower. This martensite-free region is marked by cross-hatching in both Figures 3a and b. For all other welding conditions, the peak temperature exceeds the A_1 temperature at least at the top surface as shown in Figure 3a. The results show that some austenite will form in the stir zone which may convert to martensite if the weld experiences a high cooling rate. It is, therefore, necessary to estimate the cooling rate in the stirred zone.

Figure 4 shows the contours of the numerically computed cooling rates between 1073 and 773 K for various

Table 1. Material properties of the workpiece and the tool used for numerical calculations [24].

Property	Workpiece [11]	WC-based tool [11]
ρ (kg m^{-3})	7860	19,400
k (W m^{-1} K^{-1})	$71.86 - 0.0729T + 3.09 \times 10^{-5} T^2$	$92.3 + 124.67\exp(-T/580.93)$ 92.09 for $T \geqslant 2000$ K
C (J kg^{-1} K^{-1})	$989 - \frac{490}{1+(T/902)^{7.55}}$	$128.50 + 3.41 \times 10^{-6} T^2 + 3.28 \times 10^{-2} T$
τ (MPa)	$3.4 + \frac{286.4}{1+\exp(\frac{T-935}{60})}$	57.7

Table 2. Workpiece dimension and process parameters used for numerical calculations [11].

Workpiece dimensions, mm	Tool dimensions, mm			Welding conditions	
(length × width × thickness)	Shoulder diameter	Pin diameter	Pin length	Rotational speed, rpm	Welding speed, mm s^{-1}
300 × 30 × 1.6	12	4	1.5	100–900	0.42–7.08