Experimental and numerical study of friction stir welding with double-shaft stir probe†

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1. Introduction

Friction stir welding[1] (FSW) is a new developed solid-state joining technique. FSW has been successful applied to aerospace, ship manufacturing and automobile industries. However, due to the disadvantage of the keyhole, which is caused by the probe's pulling out when circular weld is applied, NASA developed a kind of double-shaft stir probe. The stir probe can pull out with a certain velocity from the weldment when the shoulder is still rotating and advancing along the weld bead. A schematic illustrating the process of FSW is shown in **Fig. 1**.

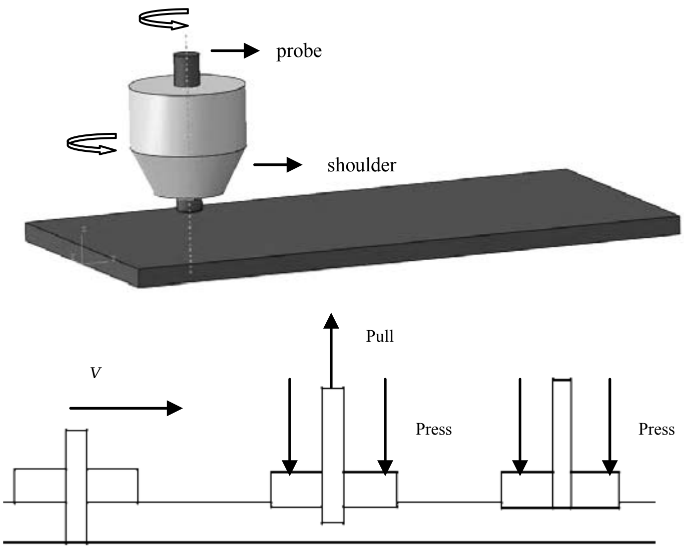

Fig. 1 Schematic diagram of friction stir welding

When the stir probe is abreast with the shoulder, the shoulder depresses at a certain velocity so as to replenish the instantaneous cavity caused by the probe's pulling out from the weldment. **Figure 2** shows the features of a weld bead in the vertical direction at the last process.

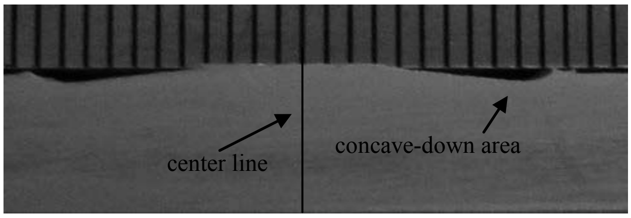

Fig. 2 Cross-section of the weld bead

Significant process has recently been made on heat transfer modeling for FSW. Frigaard, Grong, and Midling[2] developed a process model for FSW, the heat input from the tool shoulder is assumed to be the friction heat, and the coefficient of friction or the calculated temperature during the welding is adjusted to keep the calculated temperature from exceeding the material melting point. The Rosenthal equation for modeling heat-transfer for thin plates has also been applied in modeling the heat-transfer in FSW[3]. Because of the process of the probe's pulling out, the heat transfer process will become complicated. Numerical methods are very convenient for the investigation of the mechanism of FSW. Therefore, this work mainly studies the weld quality and the heat transfer.

2. Description of the heat source model

In the presented model, the heat at the tool shoulder/workpiece interface and the heat at the tool probe/workpiece interface are both considered.

Because the hardness of the probe is larger than the weldment in the FSW, when the welding is in the quasi-stable state, we can get the following equation:

$$d_f = \tau_s \times d_s$$

According to the rule of Misses yielding, the rheological shear stress τ_s can be calculated by the following expression:

$$\tau_s = 0.577 \times R_{eL}(T)$$

Where d_f is infinitesimal friction force, $R_{eL}(T)$ is the stress value when the material generates 0.2% plastic strain and is the function of temperature[4], d_s is

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infinitesimal contact area. Finally, we can get the equation of heat flux at the integral point in the tool shoulder/workpiece interface:

$$K_E = W \times 0.577\, R_{eL}(T) r$$

Where K_E is surface flux density, W is the angular velocity of the probe, r is the radial distance from the tool axis.

The friction at the tool probe/workpiece interface is simplified for calculating easily. We will treat the heat as body flux:

$$Q = 0.577\, R_{eL}(T) \times n / 30$$ [5]

Where Q is the body flux density, n is the rotating velocity of the stir probe(r/min).

Therefore, $R_{eL}(T)$ is a very important parameter related to the material property. In this experiment, Zwick machine is used for tensile test to get the Stress-Strain curve under different temperature. 2219 aluminum alloy strip is used for getting the $R_{eL}(T)$ value, as shown in **Fig. 3**. Then, the $R_{eL}(T)$ value under different temperature can be found in the curve, as shown in **Fig. 4** .

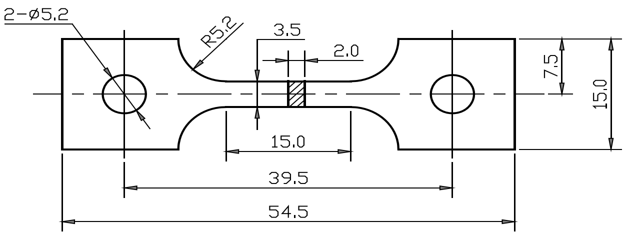

Fig. 3 Shape of samples

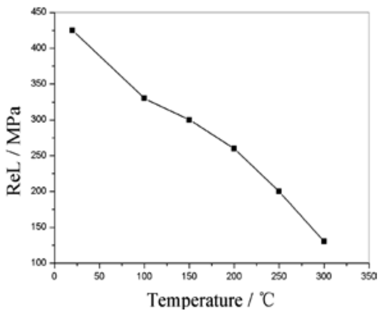

Fig. 4 2219 R_{eL} curve at different temperature

3. Temperature distribution of FSW

During this period, the tool traverses along the joint line at a constant weld speed. **Figure 5** shows the calculated temperature contour and the heat-transfer process in the weld period can be clearly found. Additionally, $R_{eL}(T)$ depends on the temperature produced by welding. Numerical models of FSW have shown that with the welding temperature increasing, the $R_{eL}(T)$ value decreases, resulting in the top temperature of some point gradually reaching. **Figure 6**, **7** show the temperature curves of three points, 12mm, 16mm, 18mm, away from the center point at the initial stage and at the end of welding respectively. From Fig. 6, it can be found that the calculated temperature contour at 12.0 s is similar to that at time 20.0s, which implies that a steady heat transfer is reached.

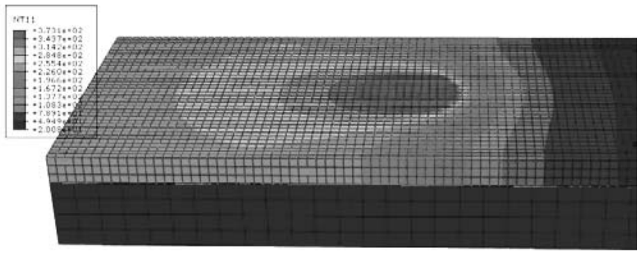

Fig. 5 3-D view of the calculated temperature contour

At the beginning and at the end of welding, the calculated temperature at the measuring points change a little, which shows the probe's primary function is to deform the material around the tool and its secondary function is to generate heat.

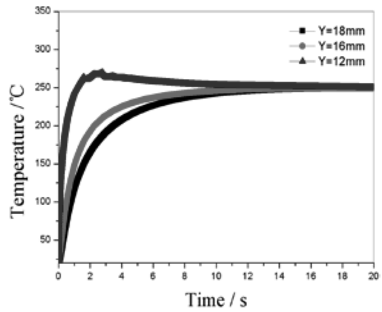

Fig. 6 Calculated temperature at the beginning

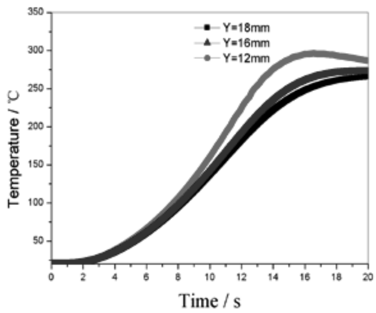

Fig. 7 Calculated temperature at the end

4. Conclusions

According to the experiment and simulation results, the following conclusions can be obtained:

（1）The self-adaption model of heat generation can accurately model the heat-transfer process in FSW. The difficulty of determining coefficient of friction has been settled. In the simulation, we adopt $R_{eL}(T)$ as an important parameter.

（2）By the FEM model of FSW welding, nodes will experience some time before reaching the top temperature. Comparing the stability period of welding with the probe's pulling out period, we find that the temperature distribution changes a little. The heat generated at the tool probe /workpiece interface accounts for 20% approximately of the total.

Acknowledgement

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