A Coupled Heat-Transfer Model for Workpiece and Tool in Friction Stir Welding

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1 INTRODUCTION

Friction stir welding (FSW) is a new solid-state welding technology invented at TWI in 1991[**1**]. This technology has been proven to be very successful in joining aluminum alloys. FSW of nickel alloys and steel is also promising [**2,3**]. FSW is successfully being applied to aerospace, automobile, and shipbuilding industries [**2-4**], and is attracting more and more research interest.

A good understanding of the heat-transfer process in the workpiece is helpful in predicting the thermal cycles in the welding workpiece and the hardness in the welding zone. Subsequently the understanding of the heat transfer process can be helpful in evaluating the weld quality. A known temperature distribution is also important for calculating the temperature-dependent viscosity when modeling the material flow in the welding.

Understanding the temperature profile in the tool is helpful in finding a method to protect the tool from being worn out in FSW, which is particularly important in welding high melting temperature alloys, such as the nickel alloys, titanium alloys, and eventually carbon steels.

Recently, significant progress has been made for modeling the heat transfer of the workpiece in FSW [**5-20**]. The thermal couple measured temperature history of the workpiece during the welding process has also been attained [**21-23**].

Chao and Qi [**5**] published a three-dimensional heat transfer model for the workpiece in 1998; in their paper, a constant heat flux input from the tool shoulder is assumed, and a trial-and-error procedure was used to adjust the heat input until all the calculated temperatures matched with the measured ones. Frigaard, Grong, and Midling [**6,7**] developed a process model for the workpiece. The heat input from the tool shoulder is assumed to be the frictional heat at the interface, 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 the heat-transfer of thin plates has also been applied in modeling the heat-transfer of the workpiece in FSW [**8,9**].

Zahedul, Khandkar, and Khan modeled the heat transfer of the workpiece for overlapping friction stir welding; a moving heat source from the tool shoulder is used [**10**].

Bendzsak, North, and Smith et al applied the CFD method in modeling heat transfer and material flow process in FSW; the material is assumed to be a kind of non-Newtonian fluid [**11,12**].

Song and Kovacevic presented a more detailed three-dimensional heat transfer model for the workpiece [**15-17**]. The heat transfer process during the tool penetration and pulling out periods has been modeled.

In the above-mentioned models, only the heat transfer to the workpiece is modeled; the coupled heat transfer to the tool is not included. Due to the fact that heat generated at the