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Elucidating of rotation speed in friction stir welding of pure copper: Thermal modeling

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In this paper, a thermal model is developed and used to simulate the friction stir welding of pure copper plates with the thickness of 4 mm in the constant traverse speed of [illegible] mm/min and five different rotation speeds. The mechanical deformation (plastic deformation) is neglected in the developed thermal model, hence the mechanical force in the process is taken to account in the heat generation equations. A moving coordinate system is used for modeling of the tool movement during the welding process. The generated heat is then used to model the grain growth in the copper plates, and consequently the mechanical properties of the copper plates. We then compare the numerical results with the results obtained from the series of experiments. Analysis of metallography images show that increasing of the rotation speed results in increase of grain size in the nugget zone, which confirmes the numerical results. Vickers hardness tests were conducted on the weld [illegible], and the maximum hardness obtained in rotation speed of 900 rpm. Results of the tensile tests and their comparison with that of the base metal showed that the maximum strength and the minimum elongation achieved again in this rotation speed. Yield strength and ultimate tensile strength increased with decrease in grain size in the nugget region and the yield strength obeyed the new proposed Hall–Petch relationship.

1. Introduction

Friction stir welding (FSW) is a quite innovative process to join metals such as aluminum, magnesium and steel alloys in the solid state. It was invented by The Welding Institute (TWI) in 1991 [1]. The process see Fig. 1 consists of a rotating tool which is plunged into two sheets or plates tightly abutted in a line, along which the rotating tool is traversed. During the process, heat is generated by plastic deformation as well as by the friction between the tool and the sample. The sample is eventually joined by the stirring action of the softened (but always solid) material. The advantages of FSW include low residual stress, low energy input, and fine grain size compared to more conventional fusing welding methods. One way to optimize the process is to utilize the thermo-mechanical modeling of FSW.

Copper, through having good thermal conductivity and a relatively high melting point, generally requires preheating treatment to maintain satisfactory penetration during arc welding, ranking as a hard-to-weld material. Like aluminum and magnesium, however, copper is basically a soft metal and can therefore be relatively easily joined by friction stir welding. Available FSW research has focused on fabrication of copper (oxygen-free copper) containment canisters for nuclear waste, fabrication of copper backing plates for sputtering devices by FSW seal welding, and some other applications, whereas FSW research on copper alloys has thus far been little documented [2].

A number of academic and industrial institutions have made efforts to develop numerical codes for FSW. Although FSW is simple in concept, the physics behind the process is complex, which includes mechanical heat generation, heat and mass transport. The large strains and strain rates make observing the details of the process difficult, which makes process modeling attractive or essential for understanding it. Colligan [3], Li et al. [4], Guerra et al. [5] and Schmidt et al. [6] studied the material flow in FSW, which is useful for the investigation of the mechanism of FSW.

A great effort was spent on the analytical models of FSW in order to formulate the heat generation. Russell and Shercliff [7] based the heat generation on a constant friction stress at the tool–matrix interface, equal to the shear yield stress at elevated temperature, which is set to 5 pct of the yield stress at room temperature. The heat input is applied as a point source or line source, and the solution is modified to account for the limited extent of the plate width. Schmidt et al. [8] formulated an analytical model for the heat generation based on different assumptions at the tool–matrix interface. Using this analytical model in comparison with experimental data, the authors suggested that a sticking or close

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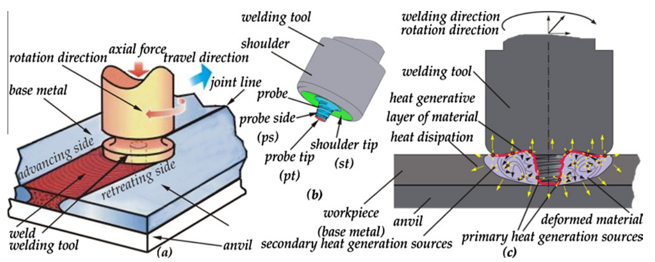

Fig. 1. Schematic of FSW: (a) principle of operation, (b) welding tool, (c) schematic of heat generation during FSW.

to sticking contact condition is present at the tool/matrix interface. The same authors presented in [9] a new thermal pseudo-mechanical model where the heat generation is described as a surface flux governed by the material flow stress which in turn depends on the nonuniform temperature at the contact tool matrix interface. In their work the solution was obtained numerically and a good correlation with the experimental data was obtained by adjusting only the heat-transfer coefficients' contact resistance. This was the first attempt to develop a thermal model where the total heat generation is not an input parameter, but is actually a result of the model itself.

FSW involves a severe plastic deformation (SPD) and dynamic recrystallization (DRX) in the nugget zone due to the stirring action of the tool pin [10]. Extensive studies on FSW of aluminum and its alloys have been reported in the literature; however studies on copper are very limited. This limitation is due to the fact that the high melting point and the high heat conductivity of copper necessitates a higher heat input to obtain a defect free copper weld. Although copper has a faced-centered cubic structure (FCC) and a good ductility, obtaining sound weld is more difficult than using aluminum and the magnesium alloys [11,12]. FSW of the copper must be conducted in lower welding speed or in higher rotation speed to increase the heat input during the process. Furthermore, not much has been published concerning the details of metallurgical and mechanical properties of the welds. Moreover, it has been shown that there were many mismatched results in the mechanical properties in the welds [13].

At sufficiently high temperatures the grain boundaries in a recrystallized specimen will migrate so as to reduce the total number of grains and thereby increase the mean grain diameter. In a single-phase metal the rate at which the mean grain diameter $\overline{D}$ increases with time will depend on the grain boundary mobility and the driving force for boundary migration. By assuming that the mean radius of curvature of all the grain boundaries is proportional to the mean grain diameter $\overline{D}$ the mean driving force for grain growth will be proportional to $2\gamma/\overline{D}$. Therefore

$$\bar{v} = \alpha M \frac{2\gamma}{\overline{D}} \simeq \frac{d\overline{D}}{dt} \quad (1)$$

where α is a proportionality constant of the order of unity, M is boundary mobility, and γ is boundary free energy. Note that this equation implies that the rate of grain growth is inversely proportional to $\overline{D}$ and increases rapidly with increasing temperature due to increased boundary mobility, M. Integration of above equation taking $\overline{D} = D_0$ when $t = 0$ gives

$$\overline{D}^2 = D_0^2 + Kt \quad (2)$$

where $K = 4\alpha M\gamma$. The boundary mobility, M, here is equal to

$$M = \frac{A_2 n_1 v_1 V_m^2}{N_a RT} exp\left(\frac{-\triangle G^a}{R}\right) \quad (3)$$

where A_2 is the probability of being accommodated in grain 2, n_1 is average atoms per unit area in a favorable position to make a jump, v_1 is the frequency of the vibrating atom, V_m/N_a is the atomic volume, and $\triangle G^a$ is the activation energy. Note that this model is derived based on the theory for an atom to be able to break away from grain 1 and being accommodated in grain 2. This simple model predicts an exponential increase in mobility, and resultant grain growth with temperature. This result should of course be intuitively obvious since the boundary migration is a thermally activated process like diffusion. Indeed boundary migration and boundary diffusion are closely related processes. The only difference is that diffusion involves transport along the boundary whereas migration requires atomic movement across the boundary.

The effect of the tool rotation speed plays an important role in the amount of the total heat input applied during the process, however this phenomenon is mostly analyzed qualitatively and the conclusions have been made based on the resultant weld defects. Therefore, the optimum range of the rotation speed will be an important parameter to achieve high quality weld, since the variation of this parameter will affect the thermo-mechanical condition for the microstructural changes in the specimen. This optimum range is affected by different parameters such as the thickness of work piece, type of alloy, geometry of the tool and welding speed. This phenomenon is analyzed and discussed here with the use of simple numerical simulations. The thermal modeling of the friction stir welding of pure copper is simulated via commercial finite element code, COMSOL.

2. Mathematical model

The heat flux in FSW is primarily generated by the friction and the deformation process. Thus, the governing equation for heat transfer in FSW is given by (Eq.4):

$$\rho c_p T + Q = \nabla \cdot k \nabla T \quad (4)$$

where Q is the volumetric heat source term arising from plastic dissipation (W/m^3), ρ is the density of materials, c_p is the mass-specific heat capacity, k is the coefficient of thermal conductivity, T is the temperature, and ∇ $(= i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y} + k\frac{\partial}{\partial z})$ is the gradient operator.

During the welding process, the tool moves along the weld joint. This movement would require a fairly complex model if one wants to model the tool as a moving heat source. In this paper a different approach is presented that uses a moving coordinate system that is fixed at the tool axis [14]. To simplify the model, the coordinate transformation assumes that the copper plates are infinitely long see Fig. 2. This means that the analysis neglects effects near the edges of the plates. Neither does the model account for the stirring process in the copper, which is very complex because it includes phase changes and material flow from the front to the back of the rotating tool. Moreover, the model geometry is symmetric around the weld. It is therefore sufficient to model only one aluminum plate.

As a result of fixing the coordinate system in the welding tool, the equation includes a convective term in addition to the conductive term, as follows:

$$\nabla \cdot (-k\nabla T) = Q - \rho c_p u \cdot \nabla T \quad (5)$$

where u is the velocity of the tool.

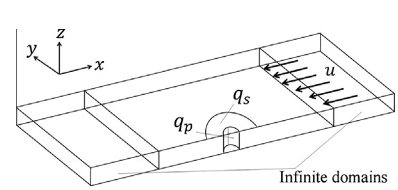

Fig. 2. Schematic illustration of the geometry used in this paper.