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Using coupled Eulerian Lagrangian formulation for accurate modeling of the friction stir welding process

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Abstract

Accurate modeling of Friction-Stir Welding (FSW) would allow a better understanding of the material flow and temperature distribution during the process. This is important for the optimization of the process parameters to avoid the conditions that generate defects in FSW. However, the numerical simulation of the process is challenging due to the numerous complexities involved in FSW. It is a fully coupled thermo-mechanical problem that includes large plastic deformation, heat flow, nonlinear contact and friction. In this study a finite element simulation with a coupled Eulerian Lagrangian formulation was used to predict the temperature distribution during the FSW process of two similar plates of AA2024. The plates were defined as Eulerian parts and the tool was defined as a Lagrangian one. The behavior of the plates' material during the simulation process was modeled using the Johnson-Cook model. In order to verify the accuracy of the results obtained from the simulation, FSW experiments were conducted with the same welding parameters. Results show good accord between the predicted and the measured temperature distributions. Furthermore, it was shown that the temperature distribution along the welding line is asymmetric with the maximum temperature in the advancing side being higher than that in the retreating side.

Keywords: Friction-stir welding; finite element simulation; Coupled Eulerian Lagrangian; AA2024; temperature distribution.

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1. Introduction

Friction-Stir Welding (FSW) is capable of joining metals that are hard to be welded, such as aluminum alloys, cooper and its alloys, titanium and its alloys, mild steel, stainless steel and magnesium alloys. Nowadays the friction stir welding technique is widely applied in many fields, such as in trains, aerospace, marine as well as in other industries. Friction-stir welding uses a non-consumable tool which has a profiled probe that is usually a little bit shorter than the required weld depth. The rotating pin tool is first plunged into the joining edge of the two clamped plates until the shoulder of the pin gets in contact with the upper surface. While still rotating the pin is then moved transversely along the joining line. The materials will be softened due to the heat generated from both plastic deformation and friction resulting in material flow from the advancing side to the retreating side. This material movement or stirring will result in a joint under solid state conditions. The quality of the weld would depend on the rotational speed, transverse speed, the depth of the tool plunging into the plate, the geometry of the tool, and the properties of the materials to be welded. Accurate modeling of FSW would allow a better understanding of the material flow and temperature distribution during the process. This is important for the optimization of the process parameters to avoid the conditions that generate defects in FSW. However, the numerical simulation of the process is challenging due to the numerous complexities involved in FSW. It is a fully coupled thermo-mechanical problem that includes large plastic deformation, heat flow, nonlinear contact and friction. The numerical simulation of FSW is still under development and different modeling techniques have been used to simulate the FSW process. The main used approaches are the Eulerian, the Lagrangian, the Arbitrary Lagrangian Eulerian (ALE), and more recently the Coupled Eulerian Lagrangian (CLE) technique. In the Eulerian method, the mesh is stationary and the material can move freely through it without element distortion. The models based on the Eulerian approach [1, 2], are mainly used for estimating the material flow and temperature distribution during the FSW process. In the Lagrangian method the temperatures and residual stresses can be estimated. However, sever mesh distortions would occur since the mesh nodes will move together with the material in such a formulation. In the arbitrary Lagrangian Eulerian approach [3-6] the mesh is not fixed in the space nor is it attached to the material. The mesh can move itself without the material thus allowing for adapting remeshing. However, the ALE approach does not model the penetration of the tool into the surface of the plates to be welded. The coupled Eulerian Lagrangian formulation exhibits advantages of both the Eulerian and Lagrangian methods [7-8]. The AA2024 alloy is difficult to weld by fusion processes and therefore is considered a good candidate for FSW studies. However, most of the studies on the FSW of AA2024 are experimental and only few are numerical. According to the authors' knowledge, this is the first study to use the coupled Eulerian Lagrangian formulation to predict the temperature distribution during the entire FSW process of two similar AA2024 plates. The plates were defined as Eulerian parts and the tool was defined as a Lagrangian one. The behavior of the plates' material during the simulation process was modeled using the Johnson-Cook model. In order to verify the accuracy of the results obtained from the simulation, FSW experiments were conducted with the same welding parameters. Results show good accord between the predicted and the measured temperature distributions. Furthermore, it was shown that the temperature distribution along the welding line is asymmetric with the maximum temperature in the advancing side being higher than that in the retreating side.

2. Material model

The material of the workpieces considered in this study is the AA2024-T351 alloy. The behavior of this material in the simulation process was modeled using the Johnson-Cook constitutive material model in which the yield stress is given by:

$$\sigma_y = [A + B(\bar{\varepsilon}^{pl})^n]\left[1 + C\ln\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_0}\right]\left[1 - \left(\frac{T - T_{ref}}{T_{melt} - T_{ref}}\right)^m\right]$$

where A, B, C, n and m are material constants, T_{ref} is the ambient temperature and T_{melt} is the melting temperature. $\bar{\varepsilon}^{pl}$ is the effective plastic strain, $\dot{\bar{\varepsilon}}^{pl}$ is the strain rate, and $\dot{\varepsilon}_0$ is the normalizing strain rate, typically 1.0/s. The values of the material constants were taken from the work of Kouadri et al. [9]. In addition to the constitutive model, other material properties such as the thermal conductivity, the coefficient of thermal expansion, the specific heat, the