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Modeling of continuous drive friction welding of mild steel

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ABSTRACT

In this study, a two-dimensional model was developed for continuous drive friction welding (CDFW) of mild steel based on the redevelopment environment of ABAQUS software. The influences of axial pressure and rotating speed on interface temperature and axial shortening were examined. The results show that increasing axial pressure, the weld interface can reach a quasi-stable temperature more quickly and the axial shortening will be larger. Similar findings were observed with increasing the rotating speed. In addition, with the increase of friction time, the interface temperature remains stable and axial shortening increases linearly with time. Experiments with mild steel bars were also conducted. The simulation results are comparable to the experiments.

1. Introduction

Continuous drive friction welding (CDFW) is a solid state joining process, in which one of the components to be welded is held stationary, while the other is rotated at a constant speed, and then the two parts are pushed against each other with an axial force. When sufficient temperature is reached at the friction surfaces, the rotating component is stopped rapidly and axial force is maintained at the same value or is increased for a short period of time. In this forging stage the hot metal cools under pressure and a weld is consolidated [1,2]. During CDFW, temperature evolution and plastic deformation of joints are the dominant processes, which determine the removal of contaminants such as oxide debris from the weld region, and thus control the weld quality.

Considering the advantages CDFW has as a high quality, high efficiency, energy saving and environmental friendly process, it has drawn to itself much attention in the last three decades. Both theoretical and experimental studies on the effects of welding parameters on joint quality have been reported in the literature. For example, Ellis [1] and Duffin and Bahrani [2] explored the weldability of mild steel at an earlier time. Sathiya et al. [3] investigated the effect of friction time on the plastically deformed region in the vicinity of the interface. Ates et al. [4] studied the effect of friction pressure on the properties of friction welded hot rolled MA95 iron-based superalloy. Ozdemir et al. [5] examined the effect of rotational speed on the interface properties of friction welded dissimilar steel joints. However, it is difficult to investigate the temperature evolution and plastic deformation of joints solely by experiments owing to the complicated coupling of thermal and mechanical effects involved in the CDFW process. The rapid advancement of computer technology has offered a new way in modeling such complex processes. It is worth mentioning that the CDFW process has been modeled by some investigators [6–11]. In particular, 1962, Cheng [6] used the analytical model to research transient temperature distributions in the process of CDFW welded similar and dissimilar materials. And the used governing equation was one-dimensional, variable thermo-physical property, transient differential equation. In 1990, Sluzalec [7] was the first to propose a two-dimensional (2D) axisymmetric finite element model computing the strain and stress fields in the CDFW components. He firstly introduced the thermo-mechanical coupled effect into the model. Midling and Grong [8] investigated the temperature evolution and plastic flow of joints during the overall CDFW process by numerical simulations and experiments. They categorized the different regions of joints as the contact zone at the joint interface, the fully plasticized region where deformation depends on rotational velocity gradient and the rates of axial and radial upsetting, the partly deformed region and the undeformed base material. Bendzsak et al. [9] and Healy et al. [10] analyzed the steady stage of CDFW by the numerical method. The analytical results were to some extent in agreement with the experiments. More recently, some researchers developed a three-dimensional finite model to simulate the CDFW process. Zhang et al. [11] made a three-dimensional (3D) simulation of continuous drive friction welding of cylinders using the DEFORM

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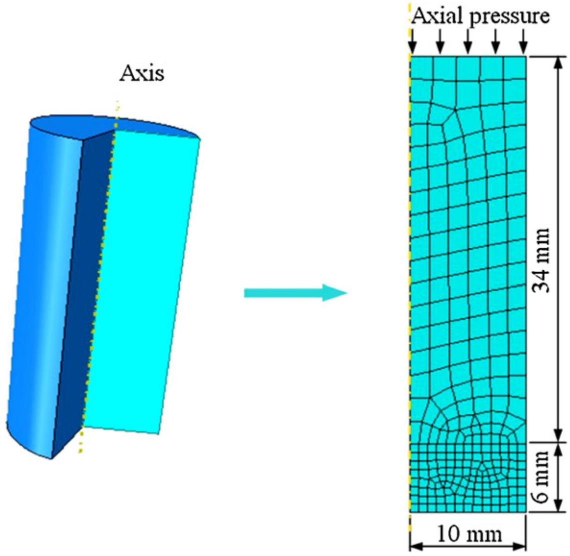

Fig. 1. 2D axisymmetric model and mesh.

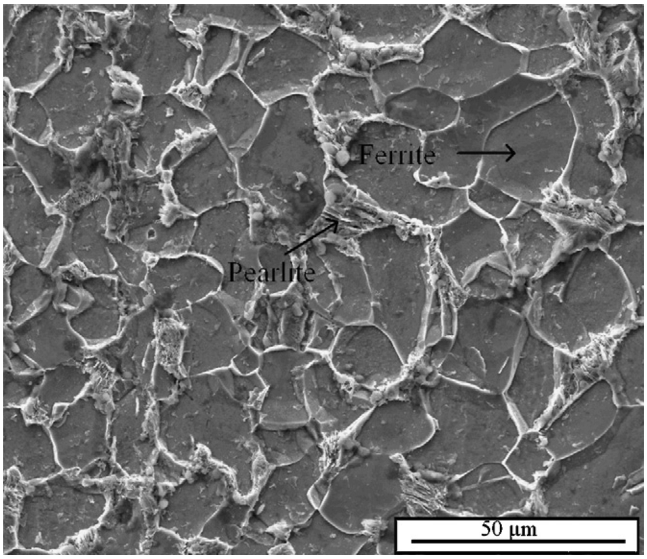

Fig. 2. Micrograph of 20 mild steel.

software. The friction force was calculated using the Coulomb friction law and shear friction law at different stages of welding. The temperature history and the final geometry of the welded joint were measured and compared with the calculated results [11].

In this study, a detailed finite element model of CDFW mild steel has been developed to simulate the coupled thermo-mechanical process with ABAQUS. The simulation results of mild steel compare well to experiments. The effects of rotating speed and axial pressure on the maximum interface temperature and axial shortening were evaluated using the developed model.

2. Numerical method

2.1. Simulation model

According to heat transfer theory, when a semi-infinite specimen has an unsteady heat conduction the affected depth x is estimated by Eq. (1) [12].

$$x = 4\sqrt{at} \tag{1}$$

where, a is the heat transfer coefficient and t is the time. In this study, we used it to estimate the possible heat affected zone to simplify the simulation model. After a careful calculation and judgment, a 40 mm length is adequate for this simulation case to reduce the amount of elements and computation time. The 2D axisymmetric model was established using the commercial software ABAQUS (Ver 6.8), as shown in Fig. 1, employing a mild steel bar with a length of 150 mm and diameter of 20 mm as in the experiment. For meshing purposes, the specimen was partitioned into two areas, where the upper 34 mm has a meshing size of 2 mm and the lower 6 mm has a meshing size of 0.8 mm (Fig. 1). Due to the extensive interfacial deformation in the CDFW process, the remeshing and map solution techniques were engaged to overcome the excessive element distortion.

The heat generation during the friction could be divided into two parts: (1) Heat generation due to plastic deformation within the joint, which can be calculated directly by defining the inelastic heat fraction as 0.9 in the software; (2) Heat flux at the interface which can be written as:

$$q = \frac{\eta\tau\omega r^2}{R} + (1-\eta)\tau\omega R \tag{2}$$

where q is the interface heat flux, η is a coefficient related to the possible pressure distribution in the interface and deviation of coaxiality, τ is the shear stress, ω is the rotational speed, r is the distance away from the axis and R is the radius of the bar.

At the beginning of friction, the material yield strength is high at a relatively low interface temperature. The classical Coulomb's friction law is adopted to calculate the heat generation, and the shear stress τ is defined as τ_f, which can be expressed as:

$$\tau_f = P/\sqrt{3} \tag{3}$$

Here, P is the axial weld pressure. A constant friction coefficient of $1/\sqrt{3}$ was used based on the following Eq. (4).

With the friction going on, the interface temperature rises quickly, and the material yield strength decreases rapidly. When the axial weld pressure is larger than the material yield stress (σ_y) at the interface, the shear stress can be described by the Von Mises yield criterion as:

$$\tau_y = \frac{\sigma_y}{\sqrt{3}} \tag{4}$$

The heat flux at the interface was conducted by using a subroutine DFLUX available in ABAQUS, which is determined by rotating speed, axial pressure and/or shear flow stress. Here, both the effects of the non-uniform linear velocity along the radial direction of specimen and the pressure distribution across the interface were taken into account. In addition, due to the continuous deformation of the object and the flash formation at the interface, Python code was developed to track and identify the "frictional" interface where heat was generated.

2.2. Material properties

The commonly used 20 low carbon steel bars were employed in the experiment. The chemical composition of 20 mild steel is 0.17–0.24 wt%C, 0.17–0.37 wt%Si and 0.35–0.65 wt%Mn. Fig. 2 shows a typical microstructure of parent 20 mild steel showing ferrite and pearlite in which the cementite and ferrite lamellae can be clearly seen. In the finite element modeling, the material conductivity and specific heat are varied with the temperature as shown in Fig. 3. The dependence of material flow stress on temperature, strain and strain rate is essential for modeling the CDFW process, thus the mechanical properties at different temperatures