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Global anisotropic response of friction stir welded 2024 aluminum sheets

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Abstract—This study investigated the global anisotropy of the friction stir welded (FSW) AA2024-T3 sheets. Different rotation speeds were used to generate welds. Uniaxial tensile tests were performed at various loading angles with respect to the welding direction. The deformation history during tensile tests was investigated by using the digital image correlation method to obtain *r*-values. Plastic anisotropy of the joints was modeled with Hill48, Yld89 and Yld2000-2d yield functions. The performance of these three yield criteria was evaluated by the comparison of theoretically calculated planar distributions of the uniaxial yield stress and the *r*-values with experimental data. Results show that the FSW joints show strong fracture and yield anisotropies. The yield stress is invariably the lowest in the diagonal direction and the highest in the rolling direction. The tensile strength and elongation are always the lowest at loading angles of 60° or 75°, rather than the commonly used 90°. The Yld2000-2d yield function can accurately describe the in-plane anisotropy of the joints compared to the other two. Rotation speed has a distinct effect on the mechanical properties of the FSW joints, resulting in evident changes in the shapes and magnitudes of the yield surfaces.

Keywords: Friction stir welding; 2024 Aluminum alloy; Anisotropy; Yield function

1. Introduction

Friction stir welding (FSW) as a promising solid-state process has led to very successful practical applications, especially in the fabrication of aluminum components and panels. This has necessitated a more deep understanding of the mechanical behavior in FSW joints. Considerable researches have been performed to determine the global and local mechanical properties of FSW joints, providing fundamental insights into the combined effect of the mechanical properties of base materials (BM) and weld zones (WZ) [1–4]. Testing specimens are generally machined perpendicular or parallel to the weld line, and then the testing results of such specimens have been used to characterize the mechanical response in FSW joints [5–7]. However, this kind of characterization cannot describe the complex mechanical behaviors of the joints (e.g. anisotropy) because of the remarkable gradient microstructures across the welds and the anisotropic grain structures. To date few attempts have been focused on the anisotropic response of FSW joints.

The asymmetric material flow, severe plastic deformation and thermal cycle that occur during the FSW process produce local microstructure changes, leading to local variations in mechanical properties near and in the weld [8–11]. For instance, Xu et al. [8] found a significant change of low-cycle fatigue along the thickness direction. The work of Nimer et al. [9] revealed that the strength and ductility of the nugget zone (NZ) were higher than that of other zones. Rao et al. [10] determined the local stress–strain curves for the BM, heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and NZ of a 3 mm thick joint by micro-tensile and indentation testing, and found steeper change in hardness and strength at the advancing side (AS) of joints compared to those at the retreating side (RS). The above results indicated the property change near and in the WZ. In addition, the materials being welded generally exhibit anisotropic grain structures and properties, especially for the rolled sheet metals [12,13]. Hence, the anisotropy in FSW joints may be a combination of the initial anisotropy and the anisotropy induced by plastic deformation and heat effect during welding. But to date it has not been well understood.

As for the structure optimization design and reliable performance evaluations (e.g. the formability of FSWed sheets and the durability or crashworthiness of FSWed automotive components), it is of great importance to properly consider the anisotropy of mechanical properties in FSWed joints because of its significant effect on stress–strain distribution. Moreover, an appropriate constitutive model should be developed to mathematically describe the mechanical responses of FSWed joints when it is subject

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to a load. The main aim of this work is therefore to characterize the in-plane anisotropy of mechanical properties in FSWed joints by uniaxial and biaxial tensile testing. In this research, three anisotropic yield functions, Hill48 [14], Yld89 [15] and Yld2000-2d [16], were chosen to describe the plastic anisotropy of the FSWed AA2024-T3 sheets.

2. Experimental details

2.1. FSW experiments

AA2024-T3 alloy sheets of 450 mm (length) × 90 mm (width) × 3.175 mm (thickness) were friction stir welded (parallel to the rolling direction) on a commercial FSW machine (FSW-RL31-010, Beijing FSW Technology Co., Ltd., PR China). Welding speed of 200 mm/min and rotation speeds of 600, 700 and 800 rpm were employed to generate different welds. The used H13 steel tool was characterized by a threaded probe with 3.4 mm in root diameter and 2.9 mm in length, as well as a concave shoulder of 10 mm in diameter. The rotating tool was tilted at 2.5°.

2.2. Uniaxial and biaxial tensile tests

Uniaxial tensile tests were conducted on the joints obtained under different rotation speeds using a universal testing machine at a cross-head speed of 1 mm/min. Specimens for uniaxial tensile tests were prepared according to the literature [13], as shown in Fig. 1. Specimens were extracted at seven different angles with an interval of 15°: 0° (welding direction), 15°, 30°, 45° (diagonal direction), 60°, 75° and 90° (transverse direction). In order to calibrate the Yld2000-2d yield function, equibiaxial tensile tests were also performed on a planar biaxial tensile testing machine with cruciform specimens.

*2.3. Measurement of the **r**-value*

Plastic anisotropy of a sheet metal is generally expressed in terms of the r-value which indicates the ability of a sheet metal to resist thinning or thickening when subjected to either tensile or compressive forces in the plane of the sheet. This parameter can be determined by uniaxial tensile tests on sheet specimens. If a material has planar anisotropy, there exists the variation of r-value in the plane of the sheet metal. In this research, the r-values at seven different angles were measured using an optical system incorporated with digital image correlation (DIC). All specimens were prepared with spray-painted black speckles on a thin layer of white paint providing a random speckle pattern for the DIC program to follow. During the uniaxial tensile tests, the deformation of specimens was recorded by the DIC system. The images recorded were analyzed with the help of an in-house code. The code selects end points for longitudinal and transverse virtual extensometers in the first image of the series. It then locates and tracks those points in the remaining images of the series to calculate the strain histories in both the longitudinal and transverse directions by Eq. (1) [13].

$$\varepsilon_x = \ln\left(1 + \frac{d_x - d_{x0}}{d_{x0}}\right), \quad \varepsilon_y = \ln\left(1 + \frac{d_y - d_{y0}}{d_{y0}}\right) \tag{1}$$

where d_x denotes the x-component of the distance between the two end points of the transverse virtual extensometer, and d_y denotes the y-component of the distance of the longitudinal virtual extensometer. Subscript 0 indicates the initial distance. Fig. 2 displays images of a specimen before and during the deformation taken by a high speed camera with the speckled pattern and virtual extensometers. Once the strain histories are obtained, the r-value can be calculated by Eq. (2) proposed by Huh et al. [13].

$$r_\theta = \frac{-k_\theta}{1 + k_\theta} \tag{2}$$

where k_θ is the ratio of the transverse strain to longitudinal strain, Subscript θ means the angle of a specimen extracted with respect to the welding direction. Detailed information on the calculations of r-values will be provided in Section 3.2.

2.4. Typical microstructure in the FSW joints

Based on microstructural characterization of grains and precipitates, a FSW joint is conventionally divided into four zones, i.e., BM, HAZ, TMAZ and NZ [3,5]. Fig. 3 shows the microstructural characteristics observed by electron backscattering diffraction (EBSD) for various zones in the case of 800 rpm. The BM exhibits a typical strip-like rolling structure containing coarse and non-uniform grains with an average grain size of ∼20 μm as shown in Fig. 3(a). The NZ, however, displays the uniform fine-equiaxed

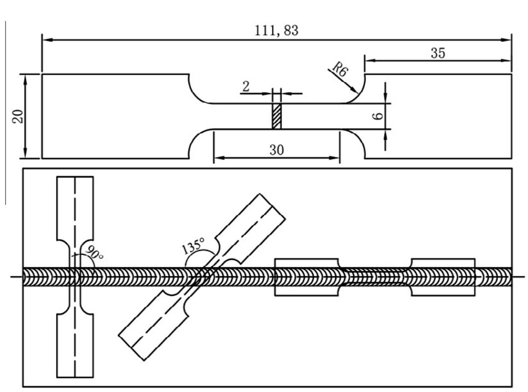

Fig. 1. Dimensions and distributions of specimens for uniaxial tensile tests.

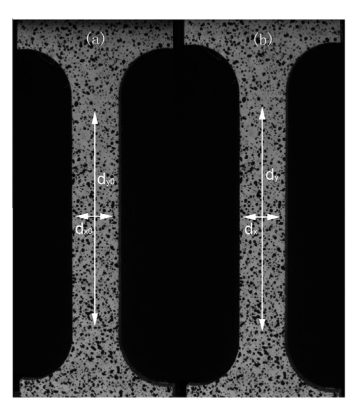

Fig. 2. Vertical and horizontal virtual extensometers (a) at the initial position and (b) after 100 s.