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Time-Dependent Residual Stress Measurements in a Severe Thermo-Mechanical Deformed Metal using Neutron Diffraction

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1. Introduction

Residual stresses are inherently introduced into materials through many thermal or thermo-mechanical processes such as welding, forming, and heat treatments [1]. Excessive residual stresses are known to be detrimental to the proper integrity and performance of components [2]. This is also the case for friction-stir welding (FSW) [3]. FSW is a solid-state joining process utilizing a rotating tool consisting of a threaded pin and tool shoulder that applies severe plastic deformation and frictional heating into the joining materials. The severely thermo-mechanical deformed materials are extruded underneath and around the tool as the tool travels along the welding line and subsequently forms a strong metallurgical joint. Although the FSW offers various advantages for joining lightweight metals and alloys, significant residual stresses are inevitable [4-6].

Considerable changes of the microstructure and mechanical properties via severe thermo-mechanical deformation have been widely studied in the FSW Al alloys [7-11]. In the FSW heat-treatable Al alloys, the hardness and yield strength were significantly varied with time due to the dissolution of the strengthening precipitates and the subsequent re-precipitation behavior under the natural aging condition. Therefore, it is suspicious that such microstructure changes and the softening/recovery of the strength can affect the variations of residual stresses. Nonetheless, direct observations of the residual stress variations are very limited in the literature.

In this study, we present neutron-diffraction results of residual stress measurements, which were performed as a function of time under the natural aging condition in a FSW 6061-T6 Al alloy. In this regard, the variations of the long-range residual stresses (type I) were determined for the FSW Al plate with time.

2. Methods and Results

2.1 Experimental details

As-received commercial 6061-T6 Al alloy rolled plates (wt% 1.0 Mg, 0.6 Si, 0.3 Cu, and balance Al) were solution-heat treated and aged for 6 hours at 185°C. The FSW sample was prepared using the plate (306-mm long × 152-mm wide × 6.5-mm thick) with about 8500 N forging force of the tool traveling parallel to the rolling direction of the plate at a constant speed of 4.7 mm/sec and tool rotation speed of 1250 rpm. The diameter of the threaded pin and the tool shoulder was 6.35 mm and 19.05 mm, respectively. Vickers microhardness (Hv) was measured at about 1 to 10,000 hours after FSW on the polished surface of the cross-section using 100 gf of the applied load. The precipitates were also observed in the completely natural aged FSW sample using TEM.

2.2 Neutron diffraction measurements

Spatially-resolved neutron strain scanning is a well-established technique [12]. It is an ideal tool for the determination of the residual stress in volume-averaged characteristics. Neutron diffraction measurements were performed using the Neutron Residual Stress Mapping Facility (NRSF2) at Oak Ridge National Laboratory. The incident neutron beam had a wavelength of 1.73 Å using a (331) Si monochromator. The scattering volume was 2 (x) x 2 (y) x 2 (z) mm^3 that was defined by a pair of incident and detector slits, Fig. 1. The incident neutron beam was diffracted from the (311) lattice plane of grains with a diffraction angle (2θ) of 90.3°. Repeat measurements were performed from about 2 hours to 10,000 hours after FSW with the same plate.

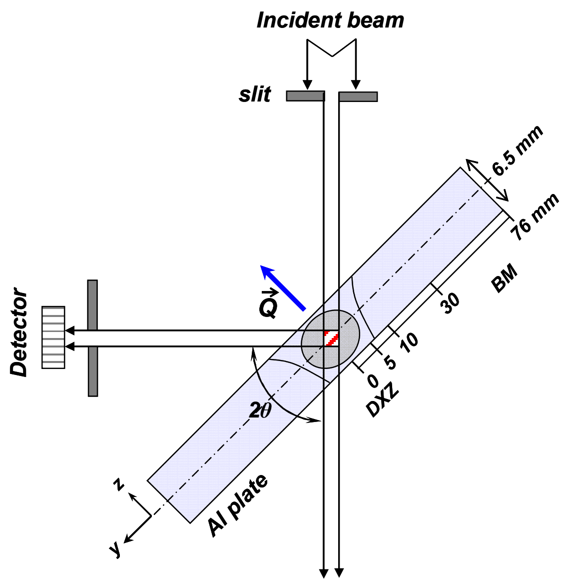

Fig. 1. Schematic of the experimental setup for the neutron diffraction measurements (DXZ: dynamic recrystallized zone, BM: base material).

For each time period, a total of 17 different locations were measured along the mid-plane of the FSW Al plate. Roughly, the region within ± 5 mm distance from the centerline of the FSW was subjected to the severe thermo-mechanical deformation and has been referred to as the dynamic recrystallized zone (DXZ) as shown in Fig. 1.

2.3 Residual stress variation at times

Figure 2 shows the residual stress changes as a function of time. Note that details of the analysis method will be described later. In the DXZ, the σ_x and σ_y show noticeable decreases (~ 25 MPa) from about 10 to 400 hours after FSW, Fig. 2(a). While, fluctuating within ± 10 MPa, no significant decreases were observed in the BM, Fig. 2(b).

Henceforth, time-dependent decreases of the residual stresses can be discussed. Since such decreases were found mainly in the DXZ, it is likely due to the microstructural characteristics of the DXZ under the natural aging condition. Figure 2(a) includes the hardness changes of the DXZ (right scale). Esmaeili *et al.* suggest the kinetics of the relative volume fraction (*fr*) of the natural aging clusters (re-precipitates) with time (t) in Al alloys using Johnson-Mehl-Avrami relationship: *fr = 1 – exp(-k•tn)* [13]. When use k = 0.06 hr^{-1} and n = 0.7, the hardness increases can be correlated with *fr* (dotted profile). Note that the *fr* starts from 0 and ends at 1 (the scale is not shown). Interestingly the residual stresses were decreased concurrently with the significant increases of the hardness (~ 20 H_v recovery) and theoretical calculation of the fr in the time range of ~ 10 to 400 hours. Meanwhile, it is clear that the residual stresses and hardness of the BM remains in the initial state, Fig. 2(b). Thus, coupled with the TEM image, it is believed that the residual stress variations are closely related to the microstructural modification (evolution of re-precipitates) in the DXZ. Note that the reproducibility of the d-spacing measurements was in the order of Δd/do ~ 5×10-5 (~ 10 MPa), which is within the error range of the experiments.

3. Conclusions

In summary, time-dependent residual stresses were measured in a FSW 6061-T6 Al alloy using neutron diffraction. A developed data reduction method allowed successful determination of the macroscopic residual stresses by separating the microstructure effects (solute variations) on the apparent- or pseudo- lattice spacings. Since the necessity of the unstrained lattice parameter was eliminated, the current method is useful for the determination of the time-dependent residual stresses. The developed tensile longitudinal stresses near the weld centerline are noticeably decreased (~ 25 MPa) at about 400 hours The variation of the residual stress is closely related to the microstructure modifications localized in the DXZ of FSW under natural aging condition.

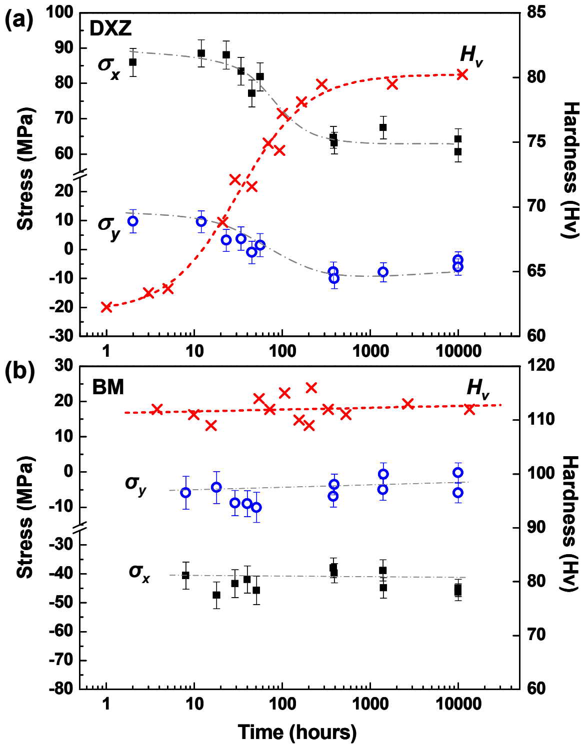

Fig. 2. Time-dependent residual stresses (σx, σy) measured at (a) DXZ (average within ± 5 mm) and (b) BM (base material, average of 30 and 50 mm). Calculated volume fraction (fr) of precipitates (dotted profile) is superimposed on the measured hardness (cross marks).

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