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On the local variation of mechanical properties in friction-stir welded 6061 aluminum alloy

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Abstract. In this work, digital image correlation technique was applied to investigate local variations of mechanical properties in friction-stir welded 6061 aluminium alloy. A pronounced strain concentration in the bottom section of stir zone was revealed during transverse tensile tests. This effect was suggested to be associated with residual stress generated in this microstructural region during friction-stir welding.

1. Introduction

Friction-stir welding (FSW) is an innovative solid-state joining technique having a very large industrial potential [1, 2]. Due to the specific character of the welding process, FSW is characterized by the sharp gradients of temperature, strain and strain rate. This normally results in drastic variations of microstructure and mechanical properties across the weld zone. So, the typical friction-stir welded joint could be considered as a very heterogeneous material.

So far, the local variations of mechanical properties in such materials were typically estimated by employing the ordinary microhardness measurements. Recently, however, an advanced digital-image-correlation (DIC) technique has been invented for this purpose [3]. The first experience of using of this approach in FSW field showed very encouraging results which enabled a significant progress in understanding of the microstructure-property relationship [e.g. 4-9].

This work is part of the wide-ranging research project intended to explore the microstructural aspects of friction-stir welded of 6061 aluminum alloy. In this particular study, the DIC technique was applied to study the local variations of mechanical characteristics of the produced welded joints.

2. Experimental

The program material used in the present study was a commercial 6061 aluminum alloy with measured chemical composition of 0.88 Mg, 0.66 Si, 0.26 Cu, 0.12 Mn, 0.12 Cr, 0.09 Zn (all in wt.%), and a balance being Al. A cast ingot of the material was homogenized at 380°C for 1 hour and then extruded to 75% of area reduction at the same temperature. To provide the peak-hardened condition, the hot extruded material was undergone to the T6 tempering treatment, i.e., solutionized at 550°C for 1 hour, water quenched and then aged at 160°C for 8 hours.

The tempered material was sliced into 3-mm-thick welding sheets and then friction-stir welded in the wide range of FSW conditions, as described in Ref. [10]. For this particular work, the weld produced at the spindle- (rotation) rate of 500 rpm and a feed rate of 125 mm/min was used. The welding tool was fabricated from a tool steel and consisted of a concave-shaped shoulder (with diameter of 12.5 mm) and an M5 cylindrical probe of 1.9 mm in length. A steel backing plate was used.



Microstructural observations were performed by using optical microscopy. For this purpose, the specimens were cut perpendicular to the welding direction, mechanically polished in a conventional fashion and finally etched with Keller's reagent. To provide a broad view on microstructure distribution within the welded joint, microhardness profiles were measured across the weld zone. Vickers microhardness data were obtained by applying a 200 g load with a dwell time of 10 s by using Wolpert 402MVD microhardness tester.

To provide a more detailed insight into local variation of mechanical properties, the DIC technique was employed. To this end, tensile specimens were machined perpendicular to the welding direction. The specimens were centered relative the weld centerline, had a gauge section of 30 mm in length and 7 mm in width, and included all characteristic microstructural zones generated during FSW. The upper and lower surfaces of the specimens were mechanically polished to achieve a uniform thickness and remove the characteristic kissing bond defect at the weld root inherent to the FSW process. For the DIC measurements, a random ink pattern was applied to the sample surface. The tension tests to failure were conducted at ambient temperature and the nominal strain rate of 10^{-3} s^{-1} . An Instron 5882 universal testing machine equipped with high speed camera was used for the tests. The in-plane Lagrangian strains were measured by using commercial Vic-3D system.

3. Results and Discussion

3.1. Microstructural observations

The low-magnification optical image of the cross-section of the produced weld is shown in Figure 1a. A distinct stir zone is seen. A relatively dark optical contrast of this microstructural area suggested significant grain refinement occurred during FSW. A characteristic basin-like shape of the stir zone evidenced a significant influence of the tool shoulder on the material flow in the upper portion of the welded joint. Another remarkable issue was a characteristic kissing bond defect which usually forms during FSW (arrow in Figure 1a). To exclude the possible influence of this defect on tensile behavior, the bottom layer of the tensile specimens was removed by mechanical polishing.

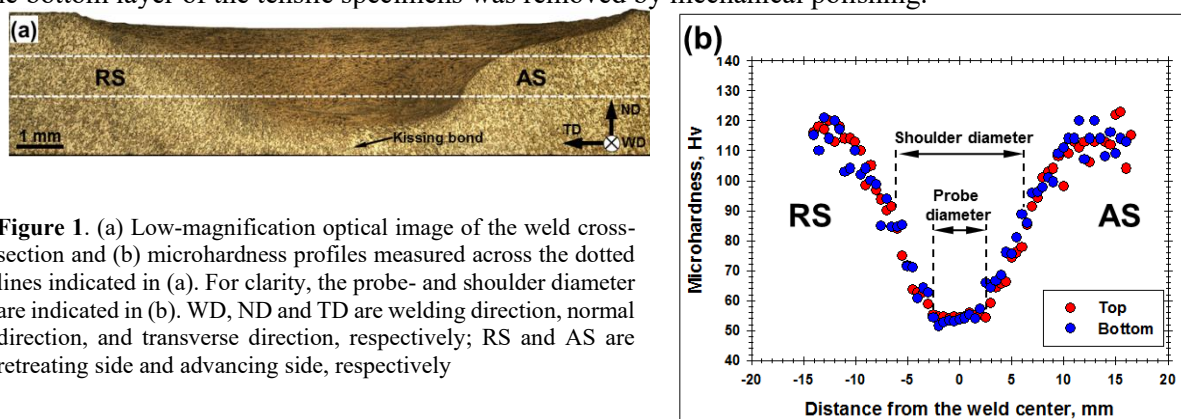


Figure 1. (a) Low-magnification optical image of the weld cross-section and (b) microhardness profiles measured across the dotted lines indicated in (a). For clarity, the probe- and shoulder diameter are indicated in (b). WD, ND and TD are welding direction, normal direction, and transverse direction, respectively; RS and AS are retreating side and advancing side, respectively

3.2. Microhardness measurements

With the aim of the preliminary evaluation of the local variation of mechanical properties within the weld zone, microhardness profiles were measured across the welded joint with the results being shown in Figure 1b. To account for the possible variation of the material properties in thickness direction of the weld, the measurements were made in its upper- and bottom sections, as indicated by the dotted lines in Figure 1a. For facilitate interpretation of the microhardness data, the probe- and shoulder diameters were indicated in Figure 1b. To the first approximation, the probe delineates stir zone whereas the shoulder diameter indicates the heat-affected zone.

It is seen that FSW resulted in essential material softening, and this effect was most pronounced in the stir zone (Figure 1b). This phenomenon is typically found during FSW of heat-treatable aluminum alloys being usually attributable to either coarsening- or dissolution of strengthening precipitates due to

the weld thermal cycle [1, 2]. Remarkably, both measured profiles showed broadly similar results (Figure 1b) thus suggesting a relatively homogeneous microstructure distribution within the stir zone.

3.3. Tensile behavior

The deformation diagrams comparing the tensile behavior of the welded joint with that of the base material are shown in Figure 2a. It is seen that the welded material exhibited a substantial degradation in both the strength and ductility characteristics. As follows from Figure 2b, this effect was associated with pronounced strain localization in relatively soft weld zone.

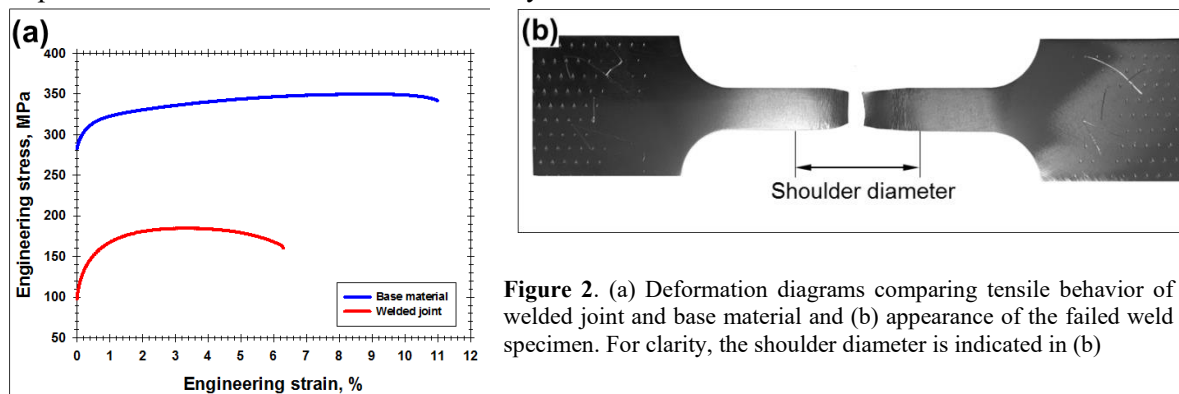


Figure 2. (a) Deformation diagrams comparing tensile behavior of welded joint and base material and (b) appearance of the failed weld specimen. For clarity, the shoulder diameter is indicated in (b)

3.4. Digital-image correlation measurements

The distribution of local longitudinal strains measured on the side surface of the welded specimen as function of global elongation during transverse tensile tests is shown in Figure 2. It seen, that the strain distribution was highly localized being almost completely concentrated in the stir zone, i.e. the softest microstructural region. On the other hand, the base material zone experienced almost no plastic strain.

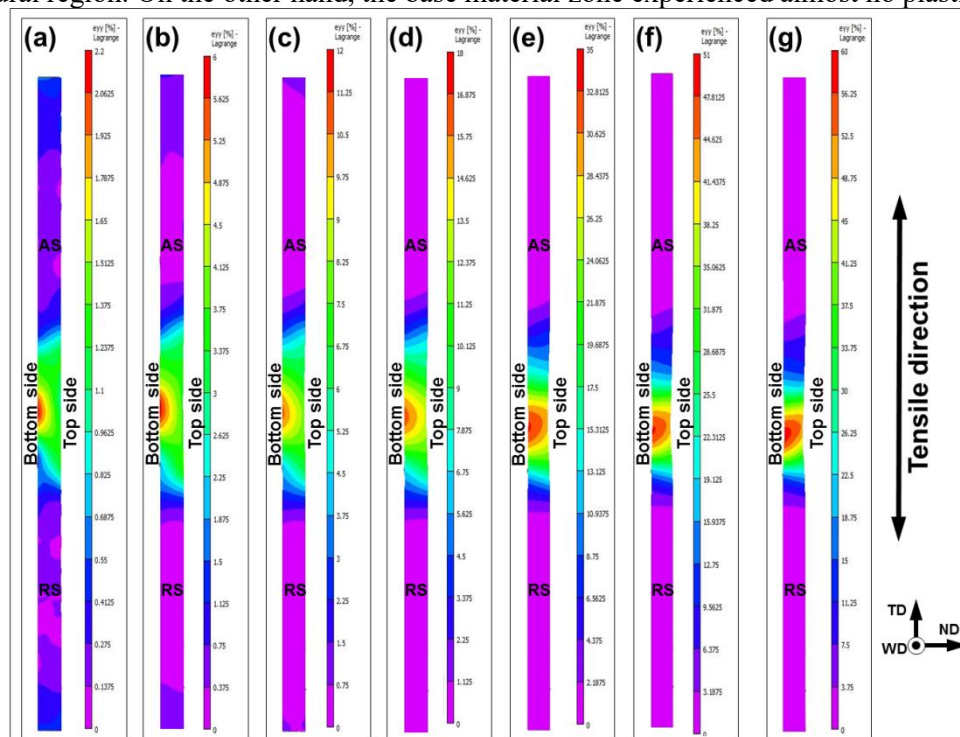


Figure 3. Distribution of local longitudinal strains on a side surface of the weld evolved during transverse tensile test after global elongation of 0,2% (a), 1% (b), 2% (c), 3% (d), 5% (e), 6% (f), and immediately before failure (g). AS and RS abbreviate advancing side and retreating side, respectively

Of particular interest was the observation that the plastic strain was most pronounced in the bottom section of the stir zone, perhaps initiating at the weld root (Figure 2a). With increasing of the global elongation, this local strain spot gradually propagated in the upward direction gradually encompassing the entire stir zone (Figures 2b to 2f). The sample failure also occurred in the stir zone, and likely also initiated from the bottom part of the stir zone (Figure 2g).

Since the “kissing bond” has been carefully polished out prior the tensile tests, it is unlikely that the revealed strain concentration at the weld root was associated with the welding defects. On the other hand, considering the microhardness measurements (Figure 1b), it is hard to believe that the above effect was associated with inhomogeneous microstructure distribution within the stir zone (though this issue still requires an additional check).

It was surmised, therefore, that the preferential strain concentration may be associated with *residual stress*. Due to the local nature of material heating during FSW, the concomitant thermal expansion of the hot material normally gives rise to the *tensile* residual stress in the weld zone [2]. As the welded sheets were placed on a steel backing plate during FSW, the weld cooling cycle was presumably governed by the heat transfer into the plate. Accordingly, the highest cooling rate (and thus the largest residual stress) should be presumably generated at the weld root. This should facilitate material flow in this microstructural region during the tensile tests and thus give rise to the strain distribution measured in the present work (Figure 2).

It should be pointed out, however, that the above suggestion is purely speculative and warrants experimental verification.

4. Conclusion

In this work, digital image correlation technique was applied to investigate local variations of mechanical properties in friction-stir welded 6061 aluminum alloy. During transverse tensile tests, a pronounced strain concentration in the bottom section of stir zone was found. This effect was difficult to explain neither in terms of welding defects nor a heterogeneous microstructure distribution. Accordingly, it was suggested to be associated with residual stress generated during FSW.

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