NEUTRON DIFFRACTION STUDY OF RESIDUAL STRESSES IN FRICTION STIR WELDS

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ABSTRACT

We report a neutron diffraction study of residual stresses in 6061-T6 aluminum friction stir welds. The specimens were 6 mm thick plates friction stir welded in the butt joint configuration at two welding speeds, 279 and 787 mm/min, respectively. The experimentally determined residual stresses show a symmetric double-peak profile across the weld center line, with the peaks located in the middle of the heat-affected zone. The maximum tensile stress, which is in the longitudinal direction, is 130 and 200 MPa, respectively. It is shown that the difference in the residual stress is due to a change in the microstructure and stress relaxation that occurred as a result of the longer heating time associated with the low welding speed. The impact of these residual stresses on the mechanical properties of friction stir welds is discussed.

INTRODUCTION

Friction stir welding is an emerging solid-state joining technique [1]. The process is illustrated in Figure 1, where a weld is formed by plunging a rotating non-consumable tool into the workpiece materials and driving the tool from beginning to finish. In the region of contact, the welding tool generates frictional heat and induces extensive plastic deformation within the workpiece materials. As the tool moves forward, the deformed materials are driven to the rear of the tool and mixed together, creating a dense, porosity-free weld zone. Because they are made by solid-state joining methods, friction stir welds are inherently immune from the cracking problems associated with solidification of liquid weld deposits. Welding related distortion is also smaller due to the low heat input and the use of fixtures during friction stir welding. In addition, high integrity welds with good mechanical properties have been made using friction stir welding for several classes of alloys which were previously deemed unweldable.

Despite the considerable progress made in recent years, the fundamental aspects of thermal-mechanical deformation in friction stir welds have not been well understood. In particular, little information is available about the magnitudes of the residual stress in friction stir welds, much less about the impact of these stresses on the mechanical properties. The low heat input and the forging force imposed by the tool in friction stir welding could lead to a very different residual stress profile than that generated by conventional fusion welding. Furthermore, the rotating tool adds a shear force in the stirred or weld zone. It is unclear how

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this shear force would modify the resultant residual stress profile. Issues like these have limited the broad use of this technology in many industrial applications.

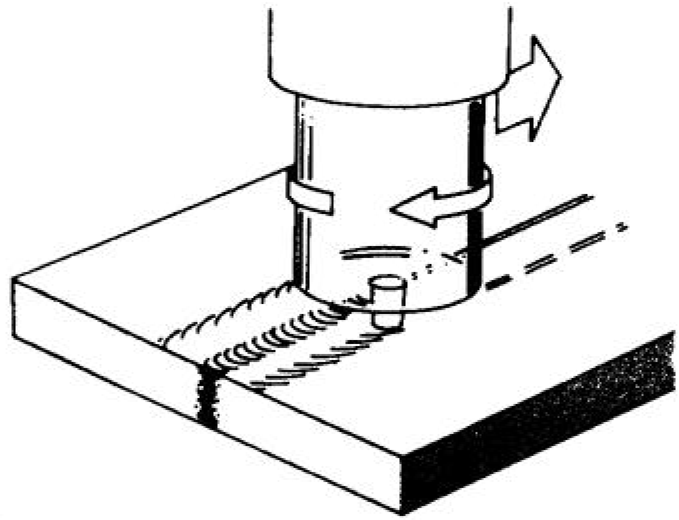

Fig. 1 Schematic illustration of the friction stir welding process.

In this paper, we report a neutron diffraction study of residual stresses in 6061-T6 aluminum (Al-6061-T6) friction stir welds made at two welding speeds (279 and 787 mm/min, respectively). Al-6061-T6 is a heat treatable wrought aluminum alloy. It has excellent acceptance of coatings and is typically used in fittings, brake pistons, computer parts, couplings, and valves. Due to hot cracking problems, fusion welding of Al-6061 alloys generally requires the use of a filler metal, whose presence modifies the properties of the welded region. However, using the friction stir welding method, high integrity Al-6061 welds have been obtained in the absence of a filler metal.

EXPERIMENTAL

The specimens were made by friction stir welding of two large (~150×300 mm^2), 6 mm thick Al-6061-T6 plates in the butt joint configuration. Two specimens were prepared with a welding speed of 279 and 787 mm/min, respectively, in order to investigate the influence of welding speed on the magnitudes of the residual stress gnereated. Coupons of 200×200×6 mm^3 were cut from each welded piece for residual stress measurements. Additional coupons were cut out of the remaining weld pieces for metallographic observations and hardness measurements.

Samples for microstructure analysis were mounted, and polished using standard metallographic procedures. The specimens were etched with Kellers reagent. Hardness profile was taken at mid-depth at an interval of 0.25 mm across the samples using LECO hardness tester with a diamond pyramid indenter and a load of 100 grams. The residual stress measurements were conducted at the High Flux Isotope Reactor of Oak Ridge National Laboratory using a modified triple-axis spectrometer. Details of the instrument have been given previously [2]. In the present experiment, a (3 3 1) reflection off an elastically bent Si crystal was used as the monochromator. The take-off angle for the monochromator was 84° and the incident neutron wavelength was 1.513 Å. A sampling volume of 2×2×2 mm^3 was used in the neutron diffraction experiment and the measurements were made on a mid cross-section normal to the weld center line. The aluminum (3 1 1) reflection was used for determination of strains. The residual stresses were derived assuming the bi-axial stress condition. For a thin plate specimen under a bi-axial stress state, the in-plane stresses can be determined without the knowledge of the stress-free lattice parameter, d_0, which in this case varies across the weld.

RESULTS

Optical micrographs taken on the metallography samples revealed four regions with distinct microstructures: (1) stirred or weld zone; (2) thermal-mechanically affected zone (3) heat-affected zone; (4) base metal. No defects were observed in any of the samples examined. The hardness data are shown in Figure 2. As in welds of other aluminum alloys in the fully aged condition, Al-6061-T6 friction stir welds also exhibit a rather complex hardness profile. Qualitatively, the hardness profiles determined for these two specimens look similar and are characterized by the presence of two pairs of a peak and a valley located on each side of the thermal-mechanically affected zone. Considerable softening was observed in the weld zone. However, the hardness in the weld and the thermal-mechanically affected zones is higher than that in the heat-affected zone. This difference is attributable to the dynamic recrystallization that took place within the weld zone as a result of the friction heat and mechanical work [3]. In the heat-affected zone, the hardness increases with increasing distance from the weld center and approaches that of the base metal (110 VHN) at 12-15 mm from the weld center.

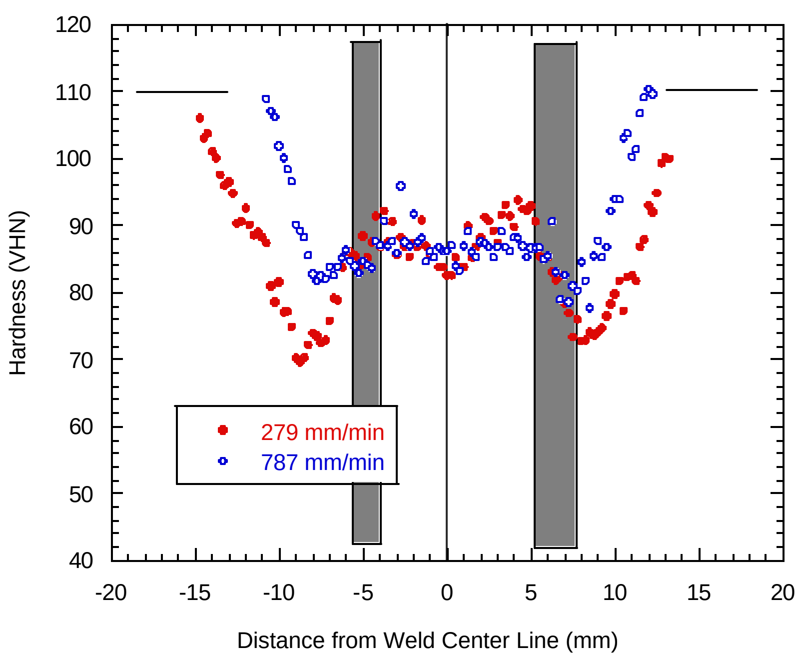

Fig. 2 Hardness profile in the vicinity of the weld zone. The base metal has a hardness of 110 VHN, as indicated by the horizontal bars. The shaded areas are thermal-mechanically affected zones and between them is the weld zone.

The residual stress in Al-6061-T6 friction stir welds exhibits a double-peak profile across the weld center line that is much similar to that in fusion aluminum welds [4-5]. The peaks are located in the middle of the heat-affected zone. For both specimens, the stress data obtained at three depths (0, and ±2 mm from mid-depth) revealed no evidence of through-thickness dependence. In addition, no apparent asymmetry was observed with respect to the weld center line, indicating that the effect of asymmetric material flow induced by the rotating tool is not evident for the two specimens under investigation. Figures 3(a) and 3(b) shows the

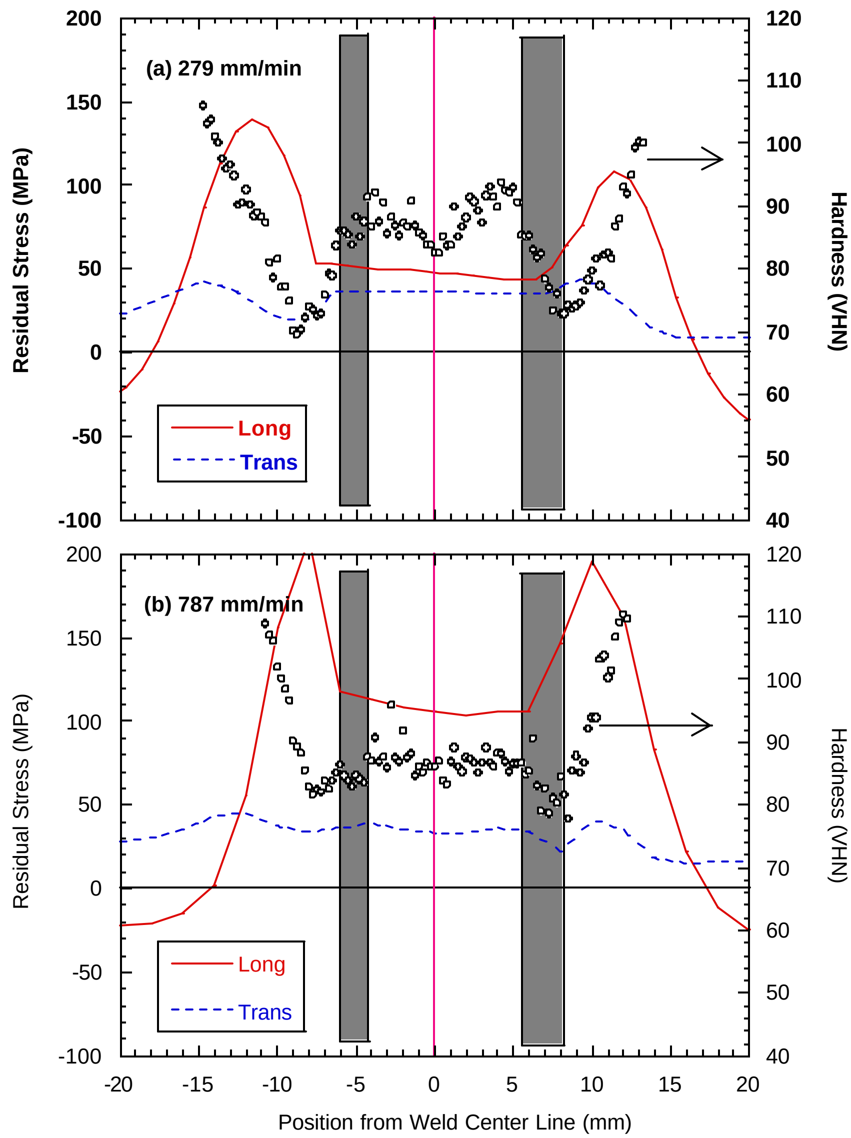

Fig. 3 Residual stress in Al-6061-T6 friction stir welds for specimens made at (a) 279 mm/min; (b) 787 mm/min. The estimated standard deviation is approximately 15 MPa.

longitudinal and transverse stress data for each specimen. The maximum tensile stress, which is in the longitudinal direction, is 130 and 200 MPa, respectively, for the 279 and 787 mm/min specimens. These stress values amount to 53% and 73% of the yield strength of Al-6061-T6 alloy, which is 276 MPa at room temperature. To facilitate discussions, the hardness data are also plotted in the figures. For both specimens, the transverse stress is small at all locations.

DISCUSSION

As can be seen from Figures 2-3, the microstructure and residual stress in friction stir welds are strongly influenced by the welding speed. Despite exhibiting similar spatial dependence, the hardness and residual stress differ significantly in magnitudes for welds made at different welding speeds. Because aluminum is an excellent thermal conductor, the longer heating time associated with the lower welding speed widens the heat-affected zone and continued heating lowers the minimum in hardness at the outer edges of the thermal-mechanically affected zone. These microstructural changes in turn affect the development of residual stresses. The extended heat-affected zone results in a redistribution of residual stresses, with reduced peak stress. The lower minimum in hardness means lower yield strength, which further limits the development of tensile residual stresses. In addition, stress relaxation occurs. This effect is readily seen when comparing the longitudinal stress in the weld and thermal-mechanically affected zones. In these regions, the longitudinal residual stress is considerably lower in the specimen made at low welding speed, even though the hardness is of similar magnitudes.

Welding speed also affects the mechanical properties of friction stir welds [6-7]. Hashimoto et al. [6] demonstrated that for a given aluminum alloy, high strength friction stir welds are obtained when the welding speed falls within a processing window. When the welding speed is too high, surface and sub-surface defects form, lowering the notch tensile strength in the weld zone. At low welding speed, the notch tensile strength is negatively affected by the formation of a softened zone. Detailed studies by North et al. [8] found that the notch tensile strength, in fact, scales with the width of the softened zone and when a small softened zone is produced, the notch tensile strength of the joint approaches that of the base metal. In a separate study, Karlsson et al. [9] noted that for Al-6082 friction stir welds, whose hardness profile resembles that of the Al-6061-T6, fracture occurs in the softest region outside the weld zone. On the other hand, for 5083 aluminum alloys, whose hardness exhibits hardly any variation across the weld, fracture was found mostly in the weld zone. Fatigue tests by Bussu and Irving [10] showed that the region of minimum hardness is also where most of the fatigue cracks were initiated. Thus, from microstructure point of view, higher welding speed produces friction stir welds with improved mechanical properties, so long as defects are not formed.

It should be noted, however, that in all of the works referenced above, the specimens were quite small in which much of the residual stresses are relaxed due to specimen preparation. In real components, where significant residual stresses are present, the influence of the residual stress cannot be ignored. The present experiment has shown that higher welding speed also leads to a higher tensile residual stress. This apparently will negate the effect produced by the less softened microstructure. To quantify the influence of the residual stress, mechanical testing results on large welded pieces are needed. Once the influence of the residual stress is established, it should be possible to optimize the welding speed, or in general welding parameters for that matter, based on a compromise between the microstructure and residual stress to produce friction stir welds with desirable mechanical properties.

CONCLUDING REMARKS

Residual stresses in Al-6061-T6 friction stir welds were determined with neutron diffraction and the influence of welding speed was investigated. The experimental data show that residual stresses in Al-6061-T6 friction stir welds exhibit a double-peak profile across the weld center line, with the peaks located in the middle of the heat-affected zone. Welding speed has significant influence on the magnitude and spatial distribution of the resulting residual stresses. The specimen made at low welding speed exhibits lower residual stress, due to a change in the microstructure and stress relaxation that occurred as a result of the longer heating time associated with the low welding speed. Further development of friction stir welding techniques requires quantitative assessment of the influence of the residual stress on the mechanical properties of welded components.

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