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Citation	Transactions of JWRI. 2015, 44(1), p. 27-30
Version Type	VoR
URL	https://doi.org/10.18910/57261
rights	
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Transactions of JWRI, Vol.44 (2015), No. 1

Friction Stir Welding of Ultrafine Grained TWIP Steel†

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Abstract

Microstructures and mechanical properties of ultrafine grained twinning induced plasticity (TWIP) steels, which were welded by both friction stir (FS) welding and conventional tungsten inert gas (TIG) welding, were studied. The ultrafine grained microstructure was successfully obtained by cold-rolling to a reduction in thickness of 88 % and subsequent annealing at a warm temperature (620 °C). Kikuchi line analysis in Transmission Electron Microscope (TEM) clarified that most of the grain boundaries in the annealed specimen are high angle grain boundaries whose misorientation angle is larger than 15 °. The TIG welding of the ultrafine grained TWIP steel produces coarse grains whose mean grain size is 70 μm. On the other hand, the joint of the FS welded sample exhibits ultrafine grains with a high density of dislocations, and retains high hardness of the base metal. These results suggest that FS welding is an appropriate process for the joining of the ultrafine grained TWIP steels. The microstructure evolution during the FSW was discussed with focus on the temperature dependence of the stacking fault energy of the TWIP steel. The tensile deformation of the parts of these joints were also examined at room temperature.

KEY WORDS: (Twinning induced plasticity), (Steel), (Friction stir welding), (Microstructure), (Ultrafine grain)

1. Introduction

It has been recently well clarified that the ultragrain refinement of materials to a mean grain size of below 1 μm produces an extremely high strength [1]. This provides a strong motivation for the study of ultrafine grained materials for structural uses. The welding of ultrafine grained materials is important for structural applications. Friction stir (FS) welding can be regarded as one of the appropriate joining processes since it can inhibit grain growth due to a lower heat input than fusion welding. Actually, several kinds of metals with ultrafine grained microstructures fabricated by the accumulative roll-bonding (ARB) process or a thermomechanical process have been successfully joined by FS welding, while maintaining a fine grained microstructure in the weld center [2-4].

This paper describes the welding of ultrafine grained TWIP steels, which are high-manganese austenitic steels and recently developed for automotive uses [4]. The significant characteristic of the TWIP steel is its low stacking fault energy (~40 mJ/m2) at room temperature [5]. In order to clarify the efficiency of the FS welding, a comparison between the FS welding and conventional tungsten inert gas (TIG) welding of the TWIP steel is described in this paper.

2. Experimental procedure

TWIP steel (31.0mass%Mn -3.1%Al -2.9%Si -0.005%C -0.004%N -0.012%S -bal. Fe) was used in this study. Ultragrain refinement was attempted by cold-rolling with a large reduction and post-annealing. The as-received sheets were cold-rolled to a reduction of 88%. The thickness of the cold-rolled sheet was 1.5mm. The cold-rolled sheets were subsequently annealed at 620 °C for 1.8 ks.

The annealed samples were butt-welded along the rolling direction (RD) by FS welding. For the FS welding, the tool had a 12mm shoulder diameter, 4mm probe diameter and 1.4mm probe length. The probe rotation speed was 400 rpm (rotation/min) with a probe traveling speed of 100mm/min. Ar shielding gas was used during the FS welding. Conventional TIG welding was also conducted for comparison.

The microstructures and mechanical properties were characterized. A Vickers hardness test was conducted along the TD to evaluate the hardness profiles at the center of the thickness. The tensile properties of the stir zone and base metals were evaluated. The tensile specimens with a 6 mm gage length and 2 mm gage width were cut parallel to the rolling direction. All tensile tests were performed using an initial strain rate of 1×10^{-3}

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Transactions of JWRI is published by Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka 567-0047, Japan

sec^{-1}.

3. Results and Discussion

Figure 1 shows the TEM microstructure (a) and the corresponding map indicating the boundary misorientation angles (b) of the base metal (620 °C annealed sample). In the misorientation map (b), high-angle boundaries whose misorientation angles are larger than 15° are illustrated by bold black lines, while low-angle boundaries whose misorientation angles are smaller than 15° are denoted by the narrow lines. The dotted lines indicate twin boundaries with Σ3 relationship (60° in rotation angle with <111> rotation axis). The TEM microstructure (a) shows equiaxed ultrafine grains whose mean grain size was 0.6 μm. Some of the grains contain annealing twins and few dislocations were present. Misorientation measurements (b) revealed that most of the ultrafine grains were subdivided by high-angle grain boundaries. These TEM characterizations clarified that the ultrafine grained microstructure is successfully obtained by cold-rolling with a large reduction (88 %) and subsequent annealing at an appropriate temperature.

Figure 2 shows the optical micrographs of the transverse sections of the ultrafine grained TWIP steels

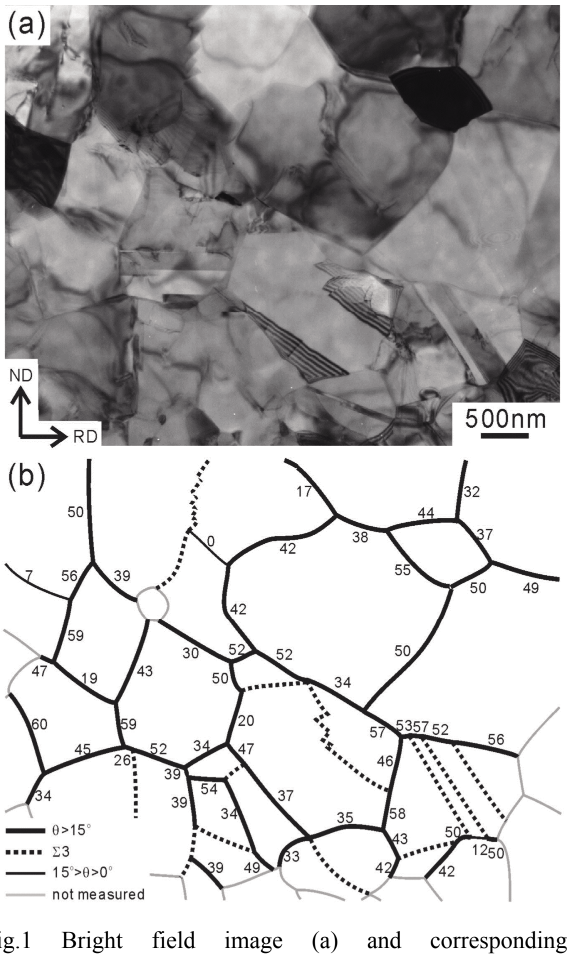

Fig.1 Bright field image (a) and corresponding misorientation map (b) of the TWIP steel 88% cold-rolling and annealed at 620oC for 1.8ks.

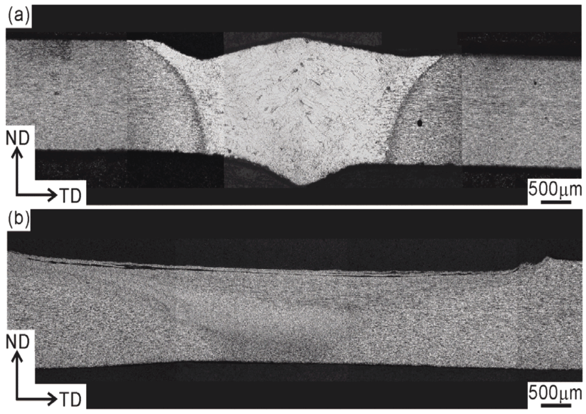

Fig. 2 Optical micrographs of the transverse sections of the welded zone in the TWIP steel. (a) TIG welding and (b) FS welding..

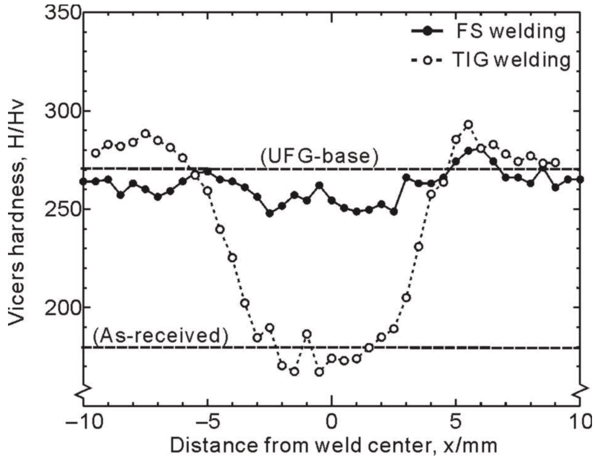

Fig. 3 Hardness profiles of FSW/TIG welded joints of TWIP steels 88% cold-rolled and annealed at 620oC for 1.8ks.

joints by TIG welding (a) or FS welding (b). Both joining centers show a high degree of continuity and no defects. The joint by TIG welding (a) shows a white-etched region with a coarse microstructure around the weld center. The width of the white-etched region along the center of the thickness is approximately 4 mm and this area is composed of huge austenite grains with elongated shape. These morphologies are typically observed in the weld metal in steel. On the other hand, in the joint formed by FS welding (b), a large difference between the stir zone and base metal are was difficult to detect.

The hardness profiles along the TD of the samples after FS welding and TIG welding are shown in **Fig.3**. The hardness of the base metal is 270 Hv. Concerning the profiles for the TIG welding, the hardness around the weld center is lower than that of the as-received samples (170 Hv). On the other hand, in the profile for the FS welding, the hardness around the weld center remains at the same level as that of the base metals with an ultrafine grained microstructure (270 Hv). These results indicate that the FS welding is the preferable process to obtain joints with a good hardness balance between the base metal and the weld center.

Figure 4 shows the microstructures in the weld center of the TIG welding (a; optical microstructure) or the FS welding (b; TEM image). The difference in the grain size corresponds to the difference in the hardness profiles. Coarse and elongated grains are observed in the center of the TIG weld. This is probably due to the large heat input. On the other hand, the joints of the FS welding (b) exhibits a fine grained structure with a high density of dislocations. It should be noted that few deformation twins evolved although twinning preferentially occurs during the plastic deformation of the TWIP steels at ambient temperature [5].

The absence of the deformation twinning in the stir zone is due to the temperature increase during the FS welding. **Figure 5** shows the relationship between the stacking fault energy and the temperature of the TWIP steels. The stacking fault energy was calculated using the thermomechanical data [5]. The stacking fault energy increases with the increasing temperature. When the stacking fault energy was lower than approximately 100 mJ/m^2, the deformation twinning preferentially takes places while the deformation twinning is inhibited when the stacking fault energy becomes higher. During the FS welding of steels, the temperature increased up to 650 °C [3] where the stacking fault energy is high enough to inhibit the deformation twinning. On the other hand, the heat input during FS welding is not sufficient for the structural coarsening into large grain sizes. Consequently, the fine grained microstructure with high density of dislocations evolves in the stir zone of the TWIP steel. The high strength in the weld center of the FS welding is caused by both the grain boundary strengthening and dislocation hardening.

Figure 6 shows the nominal stress – nominal strain curves of the base metal and the stir zone of the ultrafine grained TWIP steels. The curve of the as-received TWIP steel with a conventional grain size is also shown for comparison. The base metal of the ultrafine grained TWIP steel shows high strength and adequate uniform elongation (35%), although it was reported that the ultrafine grained interstitial free (IF) steels and aluminums have limited ductility with ultimate high strength [6]. The good strength – ductility balance in the ultrafine grained TWIP steel is probably because of the inhibited dynamic recovery due to the low stacking fault energy and an additional hardening mechanism by the deformation twinning [7]. These features enhance the high work hardening rate and prevent any plastic instability (necking). The stir zone in the joint of the ultrafine grained TWIP steel shows slightly lower strength and elongation than those of the base metal due

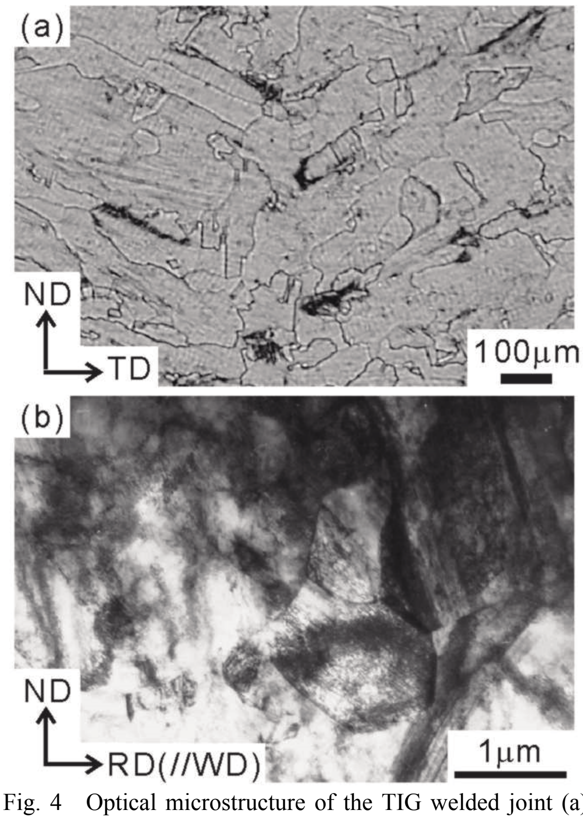

Fig. 4 Optical microstructure of the TIG welded joint (a) and TEM bright field image of the FS welded joint (b).

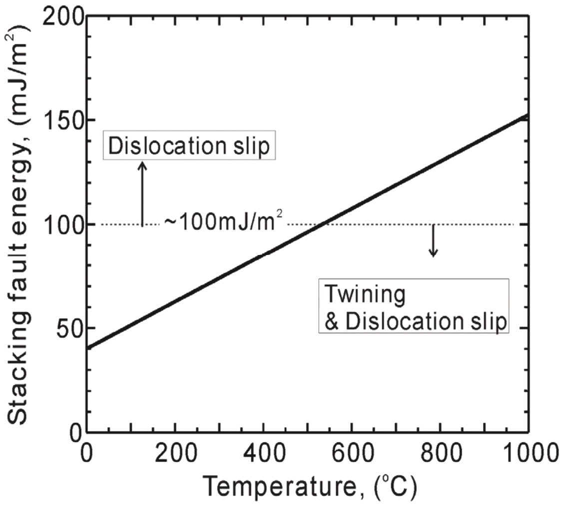

Fig. 5 Stacking fault energy of TWIP steel as a function of temperature.

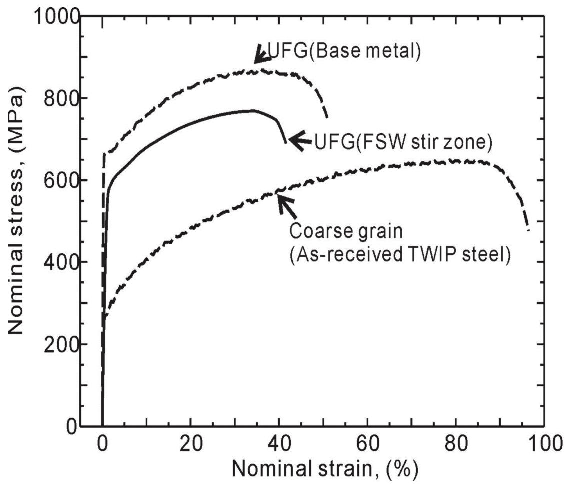

Fig. 6 Nominal stress – nominal strain curves of TWIP steels.

to the dislocations, however, it still maintains an adequate strength – ductility balance. These results suggest that FS welding is an appropriate process for joining ultrafine grained TWIP steels.

4. Summary

This study clarified that FS welding is an appropriate joining process for ultrafine grained TWIP steels because the weld center of the FS welded joint shows a good strength balance between the weld center and the base metals. Additionally, the stir zone in the joint exhibits adequate elongations.

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