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Effect of the Bidirectional Bending Process on the Microstucture and Mechanical Properties of AZ31B Alloy Welded Joints

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Abstract. The effects of bidirectional bending on the microstructure and mechanical properties of AZ31 magnesium alloy welded joints were investigated. The microstructure and mechanical properties of welded joints with and without bidirectional bending were analyzed using optical microscopy (OM), scanning electronic microscopy (SEM), transmission electron microscopy (TEM) and tensile tests. The experimental results show that bidirectional bending proves to be an effective approach to modify the mechanical properties of an AZ31 magnesium alloy welded joint. The tensile strength of the bent joints increased from 168.4 MPa to 267.1 MPa, and the elongation increased from 6.8% to 14.8% at room temperature. Twinning is the dominant deformation mechanism, in which high density twins in the upper surfaces and lower surface of the joint were formed. The grains in the joint were refined significantly by the bidirectional bending process.

1. Introduction

Among the lightest metal materials, AZ31B magnesium alloys have potential applications in reducing vehicle weight. Therefore, they offer a promising outlook in scaling down the consumption and greenhouse gas emissions in automotive and rail transportation, petrochemical, aerospace, atomic energy, and space technology industries [1-3]. However, use of AZ31B alloys is limited due to their poor ductility and formability, especially their welding performance at room temperature as a result of their hexagonal close-packed (HCP) crystal structure. Because AZ31B alloy welding performance is poor, welding defects such as porosity, cracks, and oxidation slag are easily formed, which lead to a decrease in the mechanical properties of welded joints [4-5]. Because of this, the application of AZ31B alloys is restricted, and it is urgent to improve the welding performance of AZ31B magnesium alloys. Overheated microstructures in the welded joints of magnesium alloys can cause the grains of the heat affected zone (HAZ) to experience intense coarsening, which rapidly decreases the strength and ductility of the welded joint.

Effort is being made to overcome this problem through an annealing process to modify the microstructure and eliminate thermal stress [6-7]. However, the heat treatment method is limited to improve the comprehensive performance of magnesium alloy welded joints and is not a fundamental

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strategy to solve the problem. It is known that grain refinement can improve the microstructure and enhance the mechanical properties of AZ31B alloys. Indeed, thermo-mechanical processing techniques have been explored for grain refinement to improve the mechanical properties of AZ31B alloys [8]. The study suggests that dynamic recrystallization occurs in magnesium alloy welded joints under certain conditions, which can refine the microstructure of the alloy as well as improve its ductility. W.J. Kim et al. [9] reported that the strength and ductility of AZ61 alloys were improved due to grain refinement and texture weakening induced by equal channel angular pressing (ECAP). AZ31 magnesium alloys processed by ECAP were also investigated by X. Li et al. [10]. Their results indicate that the drawing depth of the magnesium alloy sheet by ECAP at 225°C can be increased by more than 50% compared with the as-rolled condition.

The grain refinement of AZ31 magnesium alloys via equal channel angular rolling (ECAR) was investigated by B. Beausir [11]. It was found that the grain size decreased to 14 nm after the 10th pass of the ECAR process, and the hardness of the alloy increased by 53% at the 8th pass. W. Tang et al. [12] investigated the microstructure, texture, and tensile mechanical properties of AZ31 alloy sheets processed by cross rolling at room temperature. The studies suggest that the basal-type texture of AZ31 alloys can be effectively weakened; however, the ductility and draw ability were significantly improved via the cross rolling method. L.Wang and G. Huang [13] studied the evolution of the neutral layer and microstructure of AZ31B magnesium alloys by V-bending tests at temperatures from 50 to 300C. The results show that the outer tension region of magnesium alloys is dominated by slip, while the inner compression region is dominated by twinning.

However, the previous studies focused more on the magnesium alloy base metal instead of the welded joints. These processing methods are rather difficult to apply on a welded joint of a magnesium alloy. Therefore, a multi-step deformation process, such as cyclic bending, is a potentially more practical method. The multi-direction compressive deformation of an AZ31 magnesium alloy was investigated by M. Habibnejad [14]. It was found that a large number of twins can be accumulated in the alloy by small strain and multi-step bending, and recrystallization can be induced in the end. Recently, a multi-step bending and annealing process was investigated to improve the strength and malleability of an AZ31 alloy at room temperature [15]. According to the previous studies, if the welded joint can bend repeatedly at a certain temperature, the welded stress is eliminated and dynamical recrystallization occurs in the welded zone. The strength and ductility of the welded joint are improved due to grain refinement. Accordingly, the author proposes that the mechanical properties of AZ31B welded joints can be enhanced via a bidirectional bending process.

The present work is an attempt to refine the grain and enhance AZ31B welded joints' ductility by bidirectional cyclic bending deformation. In this study, a bidirectional cyclic bending deformation and annealing process was carried out to modify the grain structure and improve the mechanical properties of welded joints of an AZ31B alloy. The effect of bending on the microstructure and mechanical properties of the AZ31B alloy are investigated. The plastic deformation of the welded joints and their microstructures are also studied.

2. Experimental procedure

The initial material used for this study was an AZ31B magnesium alloy of size 200 mm × 60 mm × 2.0 mm (length ×width ×thickness) with the following chemical composition: 3.5% Al, 1.5% Zn, 0.5% Mn, 0.04% Ca and balance Mg (in wt%). The AZ31B magnesium alloy with the same chemical composition was rolled and drawn into d 3 mm wire as a filler material for welding. The butt-welded plates were made up of two plates of size 200 mm × 60 mm × 2.0 mm, and the welding was carried out by using an AC tungsten argon arc welding. Butt weld reinforcement was removed, and welded joint specimens were polished to a thickness of 1.5mm. The welded joint specimens were deformed by bidirectional bending at 423 K. Each bending and unbending was known as a pass process. The single pass strain was about 0.2, as shown in Fig.1. The convex and concave surfaces were respectively defined as the upper and lower surfaces for the first bending. The bent specimen assumed a V shape, where the angle was 120°. The guide arc radius of ejector pin was 6mm. The specimen, which was butt-welded, will be hereafter called welded joint; the welded joint that was deformed by bidirectional bending will be called bent joint.

All magnesium alloy joint specimens were prepared by electro-discharge from butt-welded plates, and were polished to remove the oxidized skin and small scratches. The tensile specimens were prepared to evaluate the yield strength, tensile strength, and elongation of the joints, as shown in Fig. 2. Uniaxial tensile tests were carried out on a universal testing machine at a constant tensile rate of 6 mm/min at room temperature.

Microstructure observations of the specimens were undertaken by optical microscopy (OM) and scanning electron microscopy (SEM). The joint specimens for OM/SEM observations were polished by the different grades of emery papers. The final polishing was done using a diamond compound (1m particles in size) in a disc-polishing machine. The above specimens were etched in a solution containing 20wt.% HNO3 and 15wt.% HF. Phase identification was carried out at room temperature via X-ray diffraction using a D-max IVA automatic X-ray diffractometer (XRD) operated under the conditions of Cu Kα, 35 kV, and 100 mA. Transmission electron microscopy (TEM) analysis was performed using a Philips CM12 operated at 120 kV. TEM thin foil specimens were prepared using a twin jet electro-polisher in a solution with 50 ml HClO4, 300 ml methanol, and 200 ml alcohol at 35 V and -223 K.

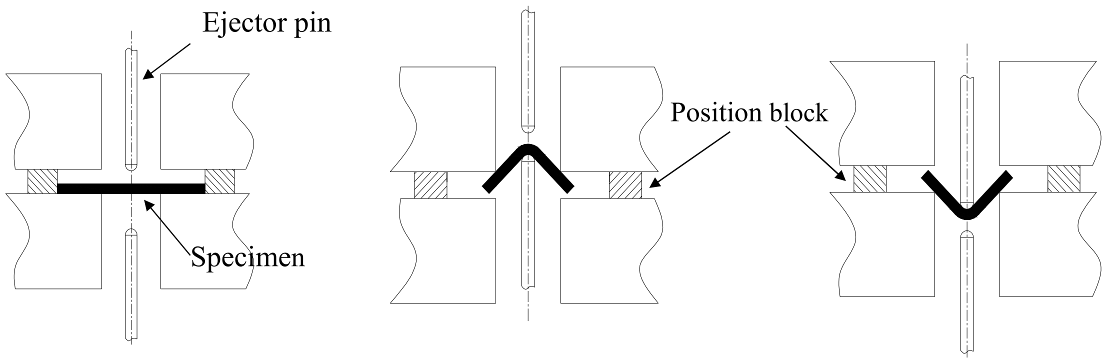

Figure 1. Schematic diagram of bidirectional bending

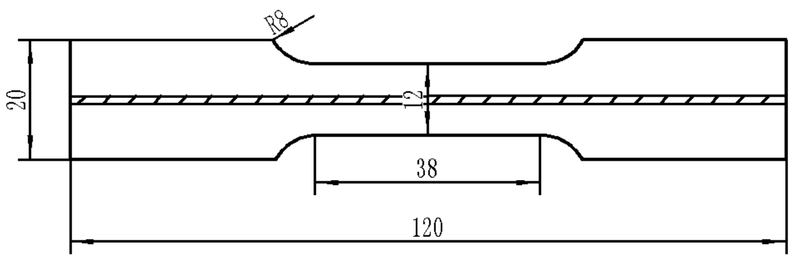

Figure 2. Schematic diagram of the tensile specimen (unit: mm).

3. Results and discussion

3.1 microstructure evolution

Fig. 3 shows the optical micrographs of the AZ31 magnesium welded joint. It can be seen that the equiaxed grains are distributed in the microstructure of the welded joint, and the average grain size is about 30 ~ 45 m. No twins were found in the welded joint. The grain size and density of the middle and bottom welded joint coincide, and the gradient grain was not found in the microstructure of the welded joint. This is mainly because the volume of the molten pool is smaller, and the whole melting pool from the top to the bottom suffered almost the same thermal cycle in the heating and cooling process. All grains of welded joints emerged at the same time in the welding process. This result is in agreement with that reported in our previous work [8].

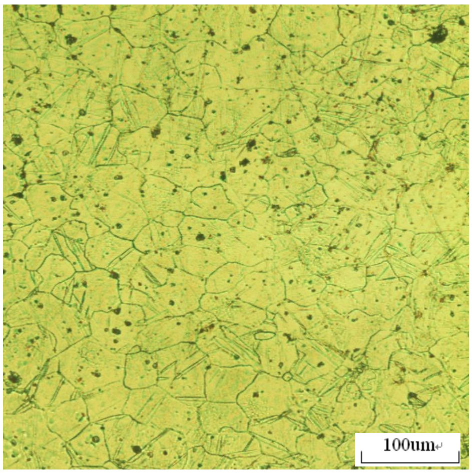

Figure 3. Optical microstructures of welded joint

Fig. 4 shows the micrographs of the bent joint with the first pass. The equiaxed grains are well distributed in the middle of the microstructure. It is worthwhile to note that no twins were found in the bent joint with the first pass. X. Huang [16] indicated that the smaller grain size restricted both contraction and tensile twinning activity. J. Li [17] also suggested that the deformation behavior mainly depends on the grain size of the microstructure at room temperature. But the twin phenomenon can be observed in the larger grains, and a number of twins occurred in these larger grains, indicated by the black arrows in Fig. 4. It is interesting to note that no twins were found in the mid-thickness region. A few compression twins appeared in the larger grain in the top and lower surfaces.

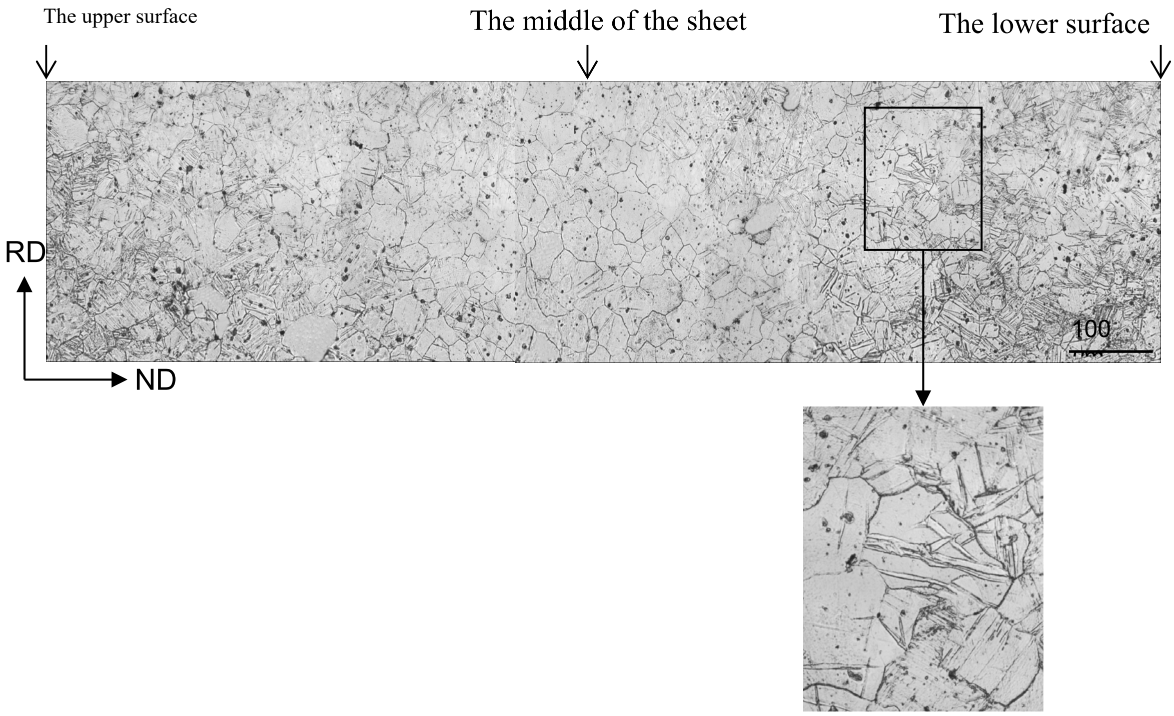

Figure 4. Optical microstructures of bent joint with the first pass

Fig. 5 shows the micrographs of the bent joint with the 4th pass, where a larger fractions of the twined grains can be observed in the top and lower surfaces, while a small fraction is present in the mid-thickness region. With the amount of deformation increasing, the volume fraction of the twin increases. It can also be seen that the volume fraction of the twins did not increase in the mid-thickness region, which is attributed to annealing during the bidirectional bending process [18-19]. It is important to note that more grain refinement occurred due to the accumulated stain. Therefore, accumulated stain is responsible for grain refinement during bidirectional bending. Increasing the number of bidirectional bending passes could enhance the energy of deformation. Also, grain boundaries and twins are enough to help promote the nucleation of new grains. In fact, at the 4th pass, it seemed that twinned grains occupied a majority of the structure by more passes of bidirectional bending due to the accumulative strain imposed by the process.

Some studies have pointed out that [20] twinning occurs in the grain, which is not conducive to slipping, and that twin deformation is also characterized by its corresponding stress concentration. In welded joints, stress concentration can easily cause twinning. To some extent, the generation of twinning can also play a role in the relaxation of stress. It is well known that twinning deformation and dynamic recrystalization (DRX) are the primary deformation modes in materials with the HCP structure [21]. The generation of dynamic recrystallization leads to grain rearrangement, grain size refinement, and the improvement of mechanical properties of joints.

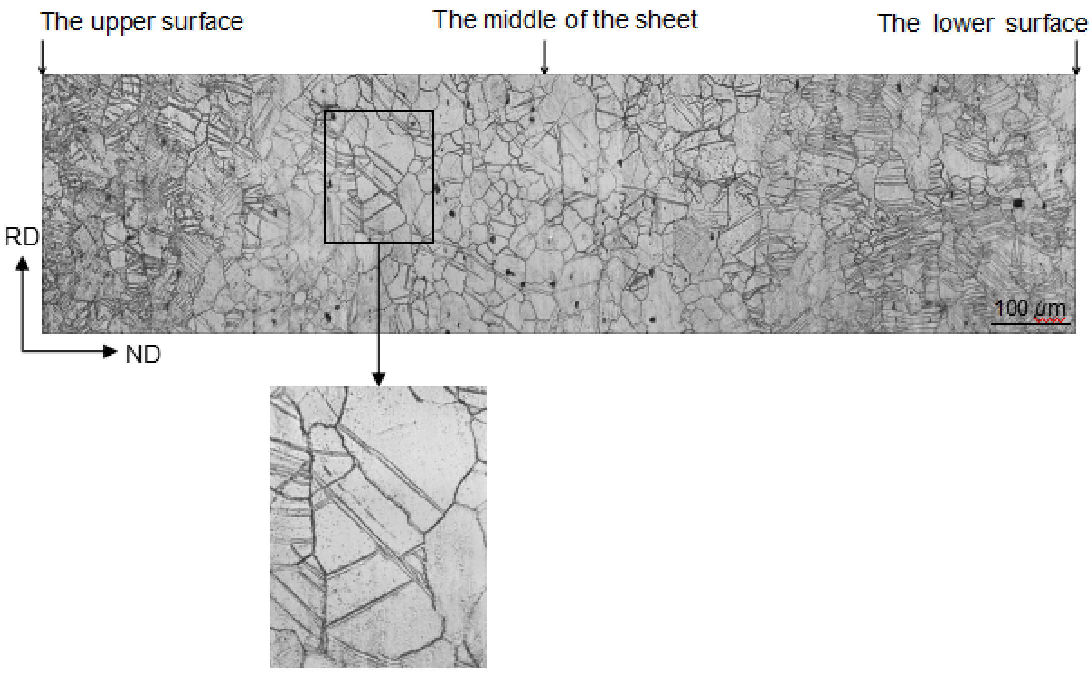

Figure 5. Optical microstructures of bent joint with the 4th pass

Fig. 6 shows XRD profiles of bent joints with first pass and with 4th pass, respectively, investigated at RT. It is known that the $(10\bar{1}2)$ and $(10\bar{1}1)$ are related to twin planes in HCP structure materials. However, $(10\bar{1}2)$ and $(10\bar{1}1)$ are confirmed in the bent joint. From Fig. 6, it can be seen that with an increase in the number of bidirectional bending passes, the intensity of the twin planes in the joint increases. As reported by J. Luo [22], twin planes are favorable for grain refinement. Moreover, the XRD profiles show that the intensity of the $(10\bar{1}0)$ prismatic non-basal planes also increased during the 4th bidirectional bending pass. The higher intensity of these planes indicates the activation of non-basal slip systems in the AZ31 magnesium alloy joint by bidirectional bending.

In several studies, the coarse and lens-shaped twins are the {1012} tensile twins, and the long and thin twins are mainly the {1011} compression twins. It is further proved that the top surface of the bent joint with first pass is dominated by compression twins.

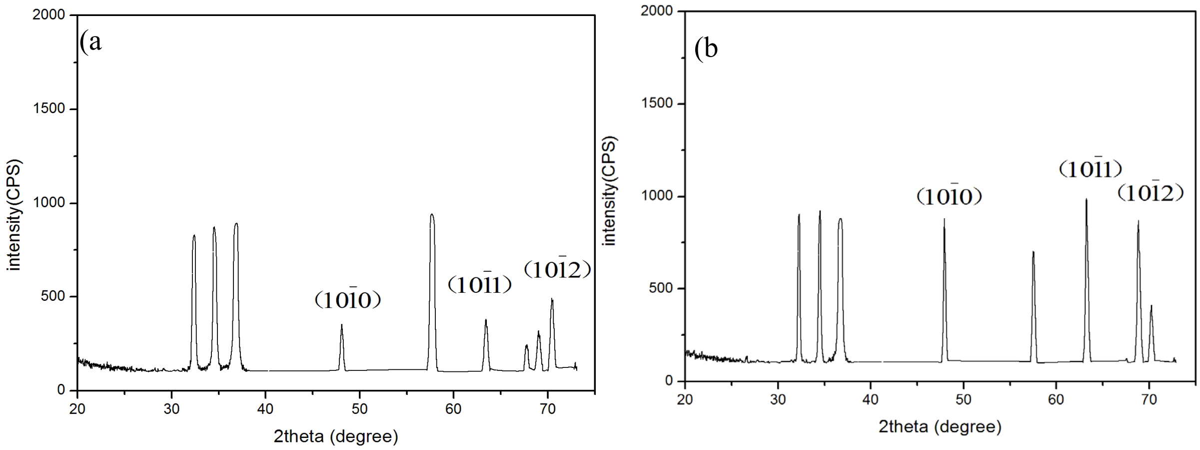

Figure 6. X-ray diffraction patterns for (a) bent joint with first pass and (b) bent joint with 4th pass

3.2 Mechanical properties

The stress-strain curves of the base metal, welded joint, and bent joint obtained by tensile tests at room temperature are shown in Fig. 7. The ultimate tensile strength (UTS), yield strength (YS), and fracture elongation (FE) are summarized in Table 1.

Comparing with the base metal, the UTS and FE of the welded joint are 168.4 MPa and 6.8%, and decreased by 33.2% and 48.5%, respectively. The decrease in mechanical properties could be attributed to coarse grains in the welded zone due to the growth of grain in the welding process. It can be seen that the UTS and YS of the bent joint are 267.1 MPa and 177.2 MPa, respectively, which are approximately 58.6% and 29.5% higher than those of the welded joint. The FE of the bent joint is 14.8%, which is two times greater than those of the welded joint. The bent joint specimen shows higher mechanical properties than the welded joint.

In the current study, the enhancement of the UTS, YS and FE can be attributed to grain refinement and twinning (Fig. 5). The basal texture of the AZ31B Mg alloys consist of two fibers: {0002}⟨2110⟩ and {0002}⟨1010⟩, but there is some variation in the welded zone due to remelting. The structure in the welded zone mainly consists of coarse grains. Therefore, the mechanical properties of the welded joint are lower than those of the base metal. During bidirectional bending, grain refinement leads to a lower sensitivity to strain localization in the form of necking, which helps the material achieve high fracture elongation without fracture. From Fig. 7, it can be seen that the FE of the bent joint has not significantly improved. The main reason is that twinning of the bent joint occurs in the top and lower surfaces. Slight dynamic recrystallization occurs in the mid-thickness region. The thickness of twinning in the surface is only 3 μm.

Microhardness values of the base metal, the welded joint, and the bent joint are shown in Fig.8. It can be seen that the microhardness (76 Hv) of the bent joint is higher than that of the base metal (65 Hv) and the welded joint (53 Hv). Studies indicate that the microhardness is significantly influenced by two factors: grain size and density of dislocation. High dislocation density and twins of bent joints increase the microhardness. Therefore, the microhardness of the bent joint was higher than that of the welded joint. In the present study, the increase in microhardness is attributed to the density of dislocation imposed by bidirectional bending. The microhardness of the bent joint is 41% greater than that of the welded joint.

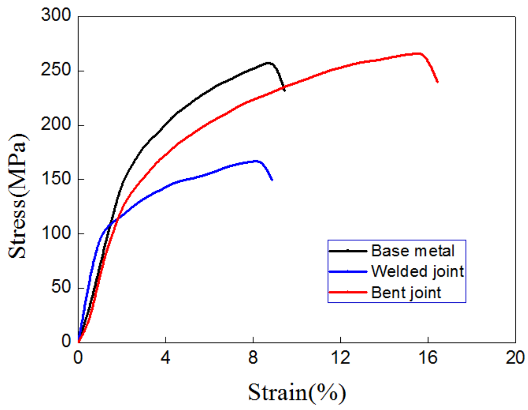

Figure 7. Stress-strain curves of specimens

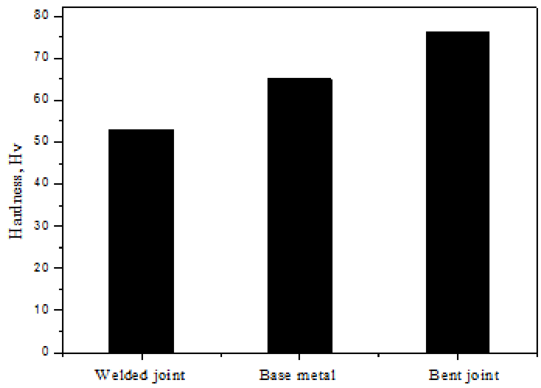

Fig.8 Microhardness of specimens

Table.1 Mechanical properties of various specimens

sample	UTS(MPa)	YS(MPa)	FE(%)
Base metal	252.1	165.9	13.2
Welded joint	168.4	136.8	6.8
bent joint	267.1	177.2	14.8

4. Conclusion
The effects of bidirectional bending on the microstructure and mechanical properties of an AZ31 magnesium alloy welded joint were investigated. The microstructural observations and tensile tests at room temperature enable us to draw the following conclusions:

1. The microstructure of the welded joint was refined and the mechanical properties increased during the bidirectional bending process.
2. Twinning was the main deformation mechanism during bending. With the amount of deformation increasing, the volume fraction of the twin increases. At the 4th pass, twinned grains occupy a majority of the structure by more passes of bidirectional bending due to the accumulative strain imposed by the process.
3. Bent joints exhibit good mechanical properties with relatively high tensile strength at room temperature. The tensile strength and elongation of the bent joint are 267.1 MPa and 14.8%, which increased by 58.6% and 117.6% compared with the welded joint, respectively.

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