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Properties and Tempering Stability of Friction-welded Joints of 700-MPa-grade Fine-grained Steel

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Friction welding (FRW) was used to weld 700-MPa-grade fine-grained steel and the changes in the microstructure state of the joints after low-temperature tempering treatment were analyzed. The results of testing show that it is advantageous to adopt a high current for welding to reduce the width of the heat-affected zone (HAZ) and minimize the size of the grain growth. The microstructures of the weld zone (WZ) and HAZ were finer than those of the base metal (BM), and the size of the grain in the HAZ was 9–11 μm. As the thermal stability of the friction-welded joints of ultrafine-grained (UFG) welding steel is low, if it is necessary to release the residual stress of joints by tempering after welding, the temperature should not exceed 300 °C.

1. Introduction

Because of the excellent strength, high toughness, and good prospects of ultrafine-grained (UFG) steel, welding is an important means of exploring its advantages. In countries' UFG steel research projects, welding has always been one of its main focuses.(1,2) In the welding of UFG steel, since its microstructure is extremely refined and the tendency of grain growth is large, UFG steel is sensitive to the welding thermal cycle and more difficult to weld than traditional steel. The coarsening and softening of the heat-affected zone (HAZ) and the local brittleness and deterioration of global mechanical properties of joints are the main problems.(3–6) In this paper, we adopt the method of friction welding (FRW) for the welding of UFG steel and analyze the changes in the microstructure and tempering stability of UFG steel joints subject to FRW.

2. Materials and Methods

The material used in this experiment was produced by microalloying and thermal mechanical control processing (TMCP). The microstructure of the workpiece was composed of

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ferrite (F) and pearlite (P). The average grain size of the base metal (BM) was about 5–7 μm. The chemical constituents of the BM are shown in Table 1. The mechanical properties of the BM are shown in Table 2.

3. Results and Analysis

The welding parameters were strictly controlled in the experiments. The experimental parameters were weld pressures of 40, 60, and 80 MPa, friction times of 1, 3, and 5 s, upset pressures of 80, 100, and 120 MPa, and upset times of 1, 2, and 3 s. The carbon equivalent of UFG steel is low, and the HAZ during welding has barely any tendency to harden. Under some working conditions, tempering is applied to release the residual stress. The tempering stability of a UFG steel friction-welded joint was studied with the temperature maintained at 100, 300, and 500 ℃ for 1 h followed by air cooling.

3.1 Microstructure of 700-MPa-grade UFG steel friction-welded joint

Under suitable welding conditions, the joint is shown in Fig. 1. The microstructure of the welded joint is shown in Fig. 2. For convenience, the UFG steel friction-welded joint is divided into four zones: weld zone (WZ), heat-force-affected zone (HFZ), HAZ, and BM. The closer the zone to the fusion line, the denser the microstructure and the finer the grains.

Table 1
Chemical constituents of BM.

Element	C	Mn	Ni	Si	P	S	V	Al
Content	0.21	1.37	0.04	0.13	0.015	0.005	0.03	0.047

Table 2
Mechanical properties of BM.

Material	Rm (MPa)	R_{el} (MPa)	A (%)	Z (%)	Hardness (HV)	A_{KV} (J)
Actual	≥ 620		≥ 22	≥ 52		
Measurement	680	590	25	67.5	218	98

(a) (b)

Fig. 1. (Color online) 700-MPa-grade UFG steel friction-welded joint.

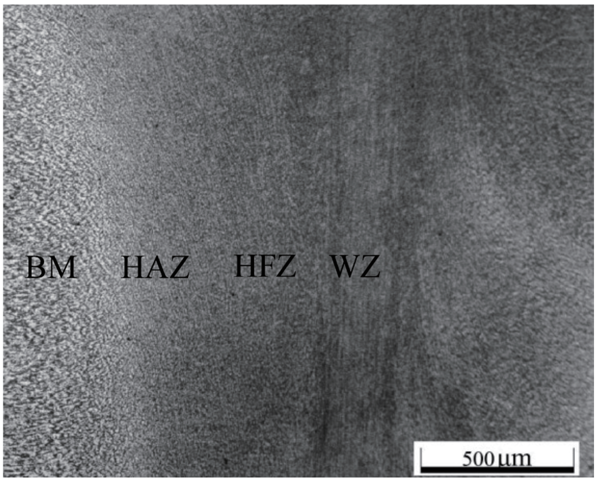

Fig. 2. Metallographic microstructure of friction-welded joint.

In the HAZ, the grain deformation along the rolling direction disappeared and the grains became isometric, but the lattice types remained the same and still consisted of ferrite and pearlite. The grain size was larger than that of the BM and about 9–11 μm. The HAZ was not affected by the friction torque. The recovery and recrystallization of the grains occurred with increasing deformation temperature. The growth of the grains is suppressed because of the high thermal cycling speed of FRW, the short residence time at a high temperature, and the effect of axial compressive stress. The dynamic recovery and recrystallization of the HFZ metal were induced by the friction torque, axial pressure, and friction heat. This zone was mainly composed of ferrite, pearlite, and a small amount of bainite. The grains in the WZ were very fine and its microstructure could not be observed using an optical microscope. Only a metal flow line, which was consistent with the radius of the workpiece, was observed in this area. This was because of the flow of the plastic metal in the radial direction under the influence of upsetting.

3.2 Tempering stability of 700-MPa-grade UFG steel friction-welded joint

The microstructures of the HAZ at different tempering temperatures are shown in Fig. 3. The tempering stability of this zone was high. Although the thermostability of the UFG steel is low, during the welding thermal cycle, the microstructure of the HAZ undergoes a normalization and a slight growth, and the stability of the microstructure and the grain size are suitable.

The microstructures of the HFZ at different tempering temperatures are shown in Fig. 4. The microstructure tempering stability of this zone was greatest when the temperature was in the range of 100–300 ℃, in which the microstructure and grain size do not change significantly. The grains began to grow when the tempering temperature reached 500 ℃. Coarse carbide appeared in this zone.

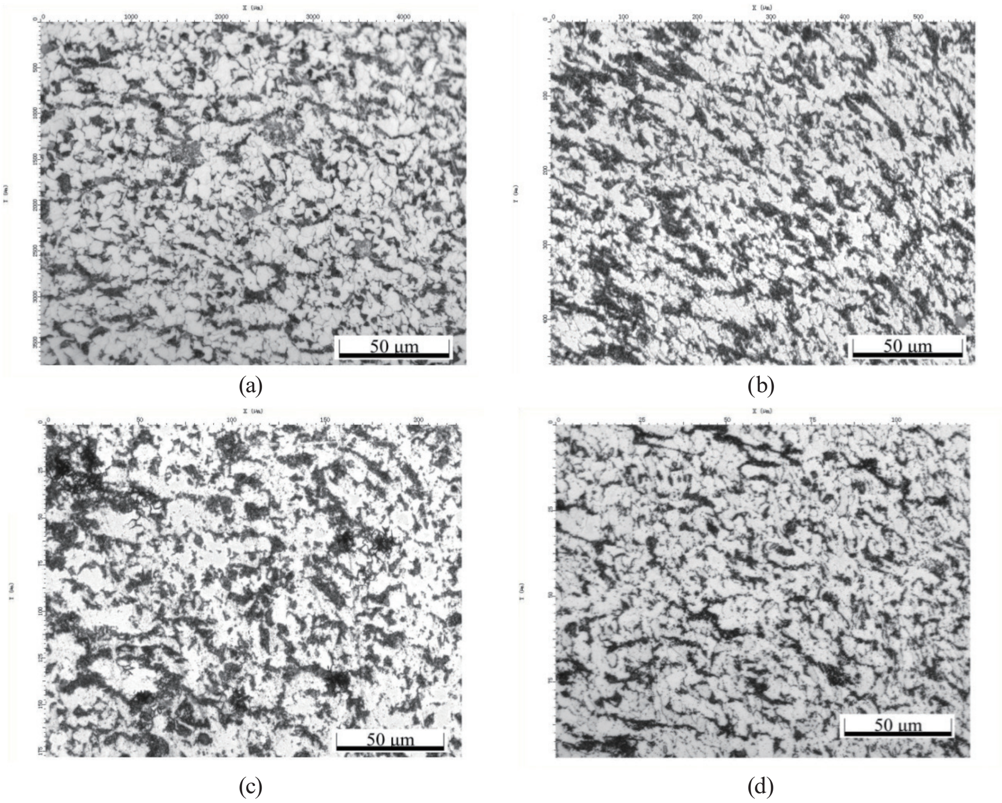

Fig. 3. Microstructures of HAZ at different tempering temperatures: (a) welding state, (b) 100 °C, (c) 300 °C, and (d) 500 °C.

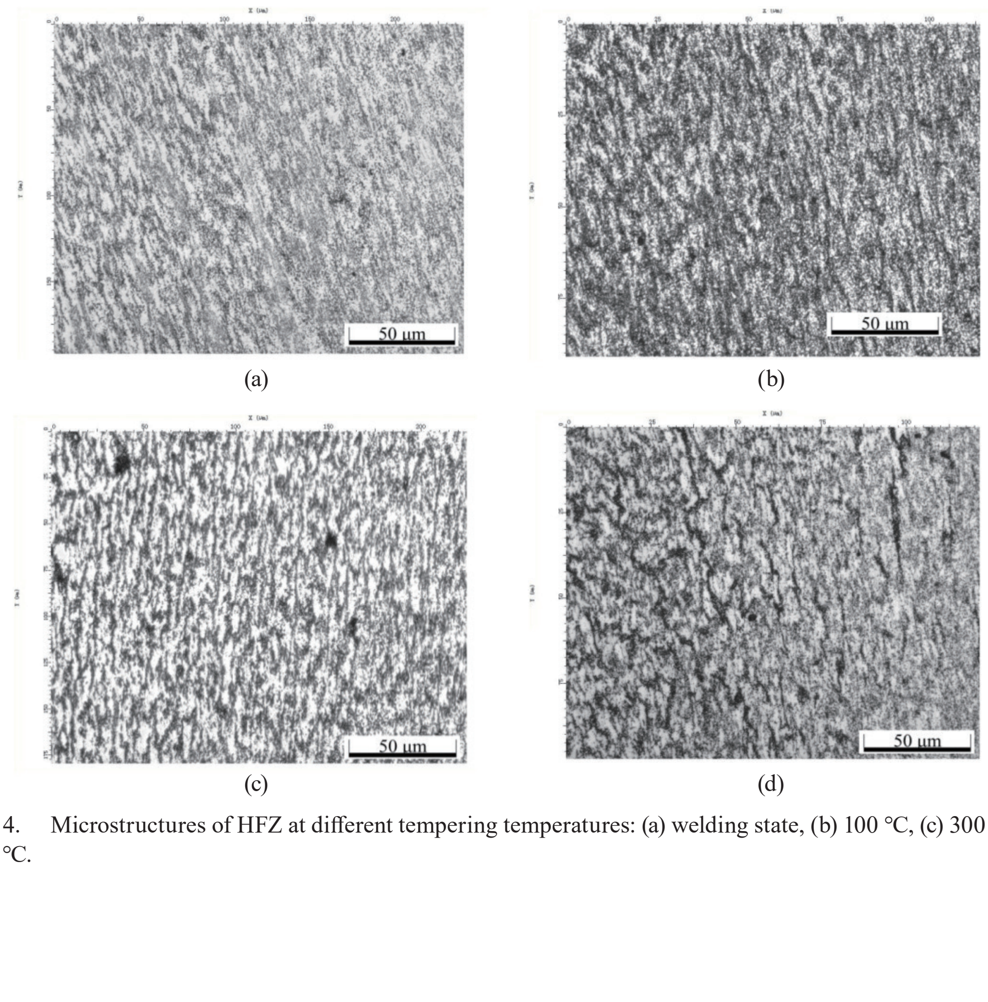

Fig. 4. Microstructures of HFZ at different tempering temperatures: (a) welding state, (b) 100 °C, (c) 300 °C, and (d) 500 °C.

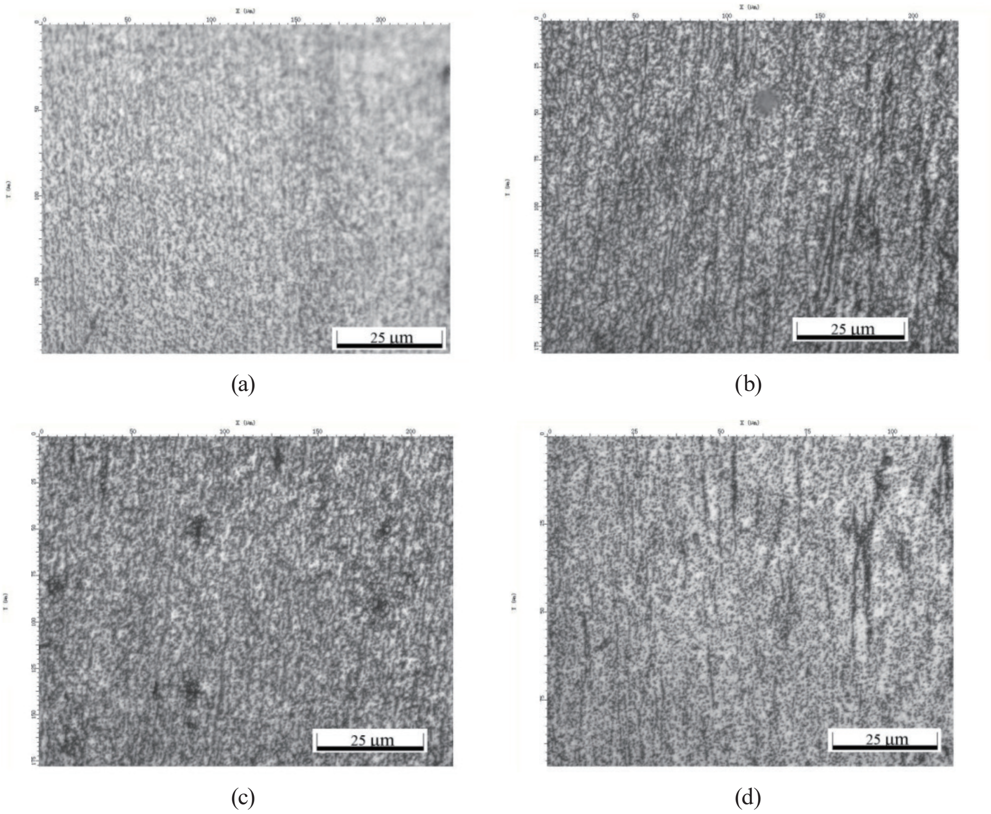

Fig. 5. Microstructures of WZ at different tempering temperatures: (a) welding state, (b) 100 ℃, (c) 300 ℃, and (d) 500 ℃.

The microstructures of the WZ at different tempering temperatures are shown in Fig. 5. The microstructure in this zone did not change significantly when the tempering temperature was lower than 300 ℃. When the tempering temperature was increased to 500 ℃, the grains began to grow, and precipitates and a banded structure were observed.

4. Conclusions

(1) The friction weldability of UFG steels is high, and it was found to be advantageous to adopt a high current for welding to reduce the width of the HAZ and minimize grain growth.

(2) A UFG steel friction-welded joint is composed of a WZ, an HFZ, an HAZ, and a BM. The microstructures of the welding line and HAZ are finer than that of the BM, and the size of the grains in the HAZ was 9–11 µm. With increasing distance from the fusion line, the hardness from the center of the weld to the BM tended to decrease, but there was a softened zone of 0.2 mm width in the HAZ.

(3) As the thermal stability of the friction-welded joints of UFG steel is low, if it is necessary to release the residual stress of joints by tempering after welding, the welding temperature should not exceed 300 ℃.

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