JOURNAL OF MATERIALS SCIENCE **39** (2004) 7119–7124 LETTERS

Analysis on the welding heat-affected zone microstructures of austempered ductile iron

DEYUAN LI
School of Material Science and Engineering, Shenyang University of Technology, Shenyang 110023, People's Republic of China

ZHENFENG ZHOU , DAQIAN SUN
Institute of Material Science and Engineering, Jilin University, Changchun 130025, People's Republic of China

Austempered ductile iron (ADI) is a kind of high strength ductile iron. It possesses a high level ultimate strength of 800–1200 MPa and a elongation 3–10% simultaneously. ADI casts usually have an austenitic-bainitic matrix obtained by austempering heat treatment. In 1971 the material came into existence in Czechoslovakia, and has since been widly used in industry [1]. When the ADI castings need to be produced and repaired, sometimes the welding procedure is necessary. By controlling the composition and cooling rate of the weld metal, a austenitic-bainitic microstructure can be directly obtained under as-welded conditions [2]. In previous study, the welding electrodes used for ADI were studied and the microstructures of the weld metal were analyzed [3, 4]. However, during the welding procedure the base metal near the weld would be heated to high temperature to form a unavoidably heat-affected zone (HAZ). The compositions of the HAZ are the same with the ADI base metal and cannot be adjusted by adding alloy element. Therefore its as-welded microstructure and mechanical properties may be different with weld metal and ADI base metal. Commonly the toughness of a HAZ is poor and welding crack is liable to arise in the zone, which may greatly damage the mechanical properties of the whole weld joint. In order to make clear the effect of the welding heating cycle on the microstructure and mechanical properties of the HAZ, the microstructures of the weld joint are observed under the optical microscope and electron microscope. The phase transformation and characteristics of the microstructure in the weld joint are analyzed.

In the test, ADI test plates with dimensions of 140 × 80 × 15 mm were used. The plates were austenitized at 900 °C for 60 min, then were austempered at 375 °C. A test hole with 40 mm in diameter and 10 mm in depth was machined at the center of the plate. Test electrodes were used to fill the test hole, the chemical composition of which is given in Table I. It has been proved that the as-welded microstructure of the weld metal would be bainite plus austenite [5]. As the cooling rate could be affected not only by the diameter of the test hole but also by the welding heat input, the welding process variables needed to hold constant during the welding procedure. The welding current was about 190 A and the voltage was about 24 V. After welding the test plate was cut off at the center of the test hole to get a specimen of the welding joint. The microstructure of each zone in the weld joint was observed under a microscope. In order to make clear the temperature distribution at the welding joint, several holes were drilled at different locations of the ADI welding joint, and thermal couple was installed into each of these holes. Temperature at each couple was measured and recorded when the test plate was welded. The distribution of highest temperature in the welding joint is plotted in Fig. 1. In the figure, the first number in each bracket represents the distance of the thermal couple to the welding fusion line and the second represents the highest temperature there. These points are linked to show the highest temperature distribution in the welding joint. In the figure, the temperature of the solidus line is indicated by line S, the upper limit, and lower limit temperature of the eutectoid temperature interval are indicated respectively by line $AC_{1.2}$ and $AC_{1.1}$. By these means the welding joint is divided into five zones: the weld zone, the partial fusion zone, the austenite transformation zone, the repeated transformation zone, and the base metal. These zones are also indicated in Fig. 1.

Fig. 2 shows the microstructure of the weld zone. As a lot of alloy elements (such as Ni and Mo) were added in

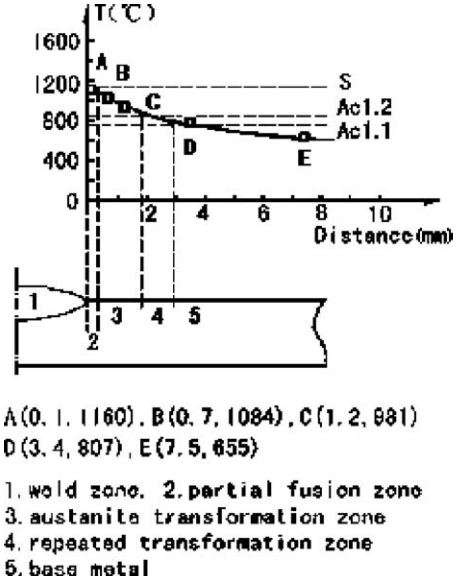


Figure 1 The highest temperature distribution across the welding joint.

TABLE I Chemical compositions of weld metal (wt%)

C	Si	Mn	Ca	Ba	Al	Bi	S	P	Ce	Ni	Mo
3.54	3.30	0.35	0.002	0.006	0.45	0.004	≤0.015	≤0.015	0.016	8.10	0.20

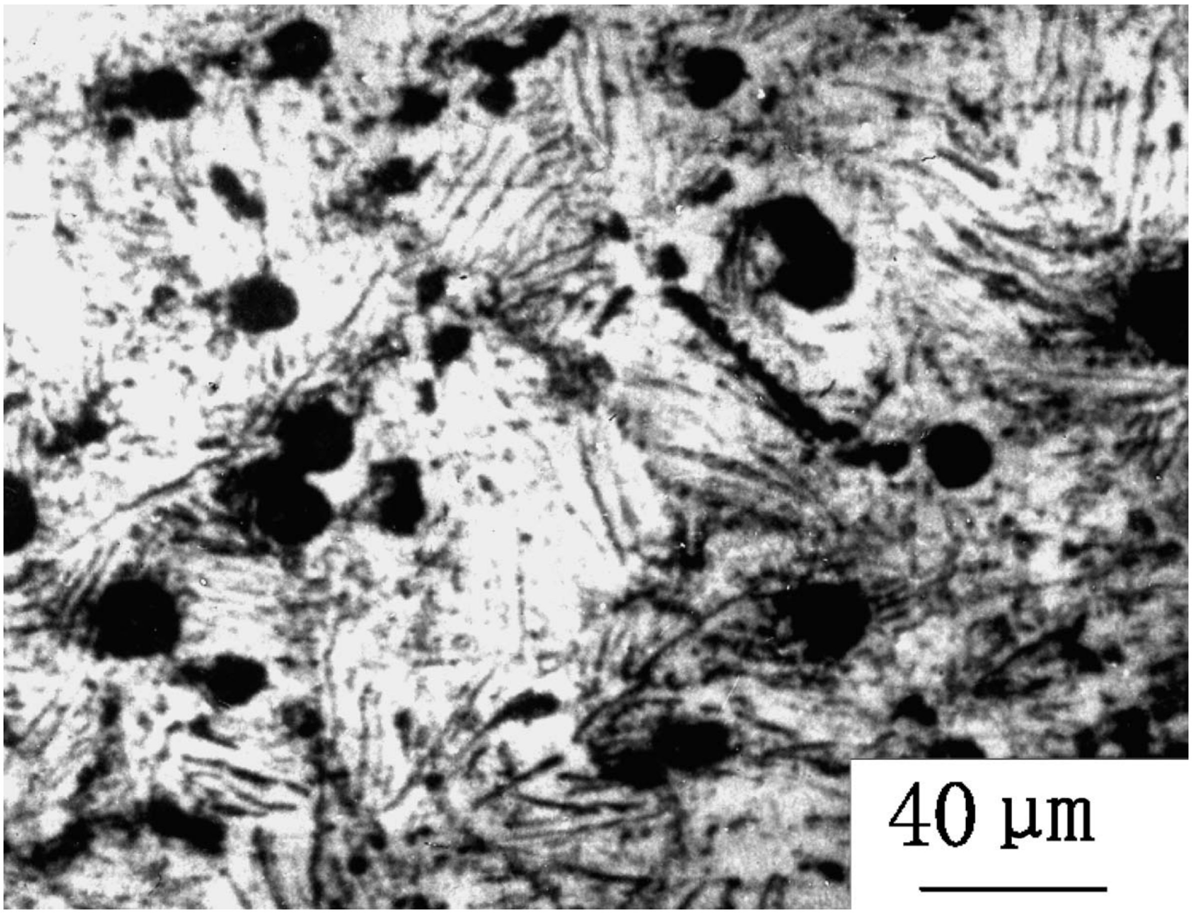


Figure 2 Microstructure of the weld zone.

by the electrodes, a matrix of austenitic-bainitic could be obtained in the as-welded condition. The microstructure of partial fusion zone is shown in Fig. 3. It can be seen that the microstructure in this zone consists of nodular graphite, pearlite, and a little of martenisite. The martensite usually appears near the fusion line. As the cooling rate in the zone is extremely fast and the alloy element in the weld metal such as Ni and Mo may be diffused to the zone, which may promote the formation of the martensite. As the arc is usually ignited at the bottom of the test hole when it was filled with electrodes and the temperature of the test plate is rather lower at this time, the rapid cooling can make carbide appear in this position. When preheating was adopted, the formation of the carbide can be avoided, but martensite cannot be totally eliminated. Fig. 4 shows the microstructure of the austenite transformation zone. The highest heating temperature in the zone is higher than the upper limit temperature of the eutectoid temperature, and lower than the temperature of the solidus line. During weld heating the matrix microstructure obtained by austempering heat treatment has transformed to austenite. On the subsequent cooling, the austenite may entirely transform into pearlite and sorbite. Thus the final microstructure in this zone will consist of nodular graphite plus paerlite or sorbite. The pearlite microstructure was observed under transmission electron microscope (TEM), see in Fig. 5. As the hardness of the pearlite microstructure is lower than that of the austenitic-bainitic microstructure, a soft-zone may appear here. Its hardness is the lowest within the whole welding joint, and is only about HV235. Fig. 6 shows the microstructure of the repeated transformation zone. The maximum heating temperature in the zone lies between the upper limit and the lower limit of the eutectoid temperature. As the temperature range is quite narrow and as the heating rate is very rapid during the welding, only a part of austenitic-bainitic matrix can transformed to austenite, that is to say, a part of bainite in the austenitic-bainitic matrix transforms to austenite. During the following cooling all the austenite will transform to pearlite, the untransformed bainite will remain same at room temperature. When bainite undergoes heating to a temperature up to 800 °C, its appearance may change to some extent. The transformation can be seen from Fig. 7. It can be seen from Fig. 7a that bainite plates begin to dissolve in the austenite at 800 °C, and these plates will disappear at 850 °C to transform to a

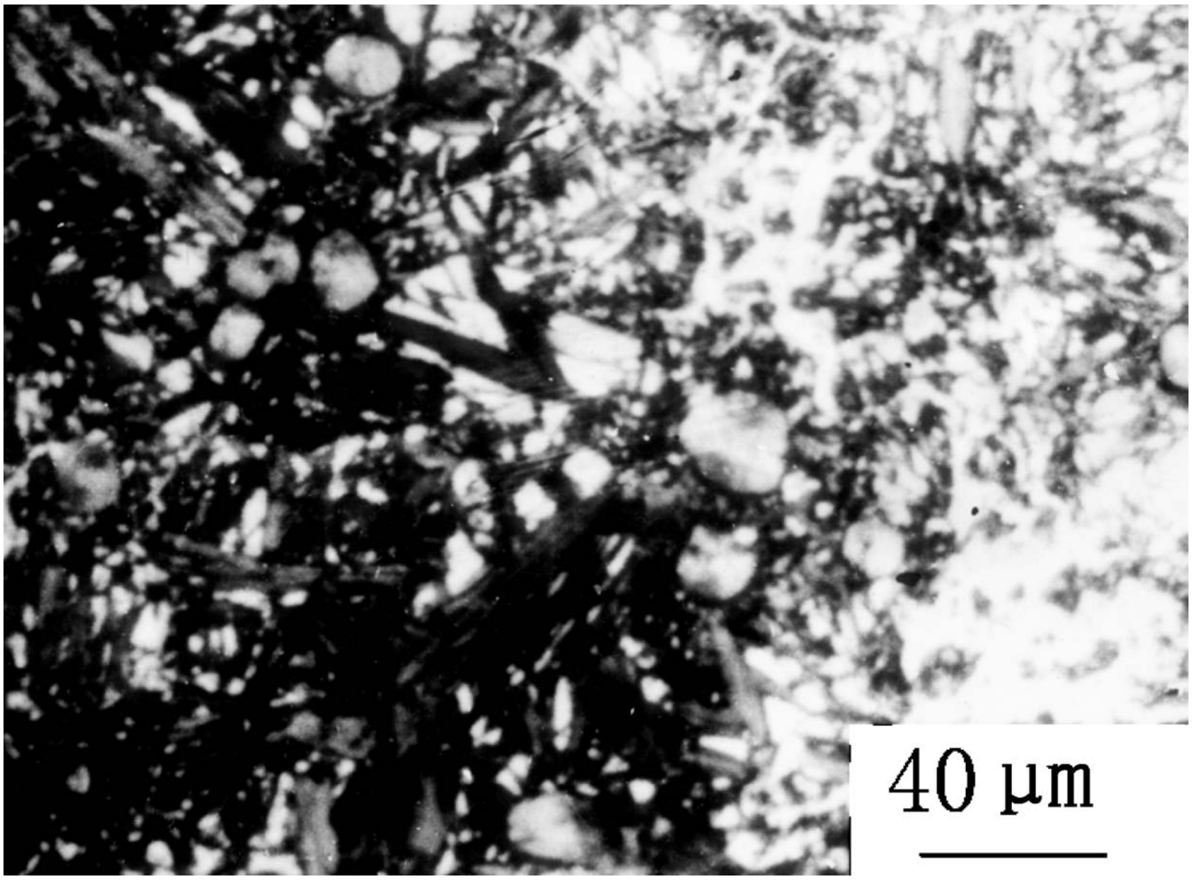


Figure 3 Microstructure of partial fusion zone.

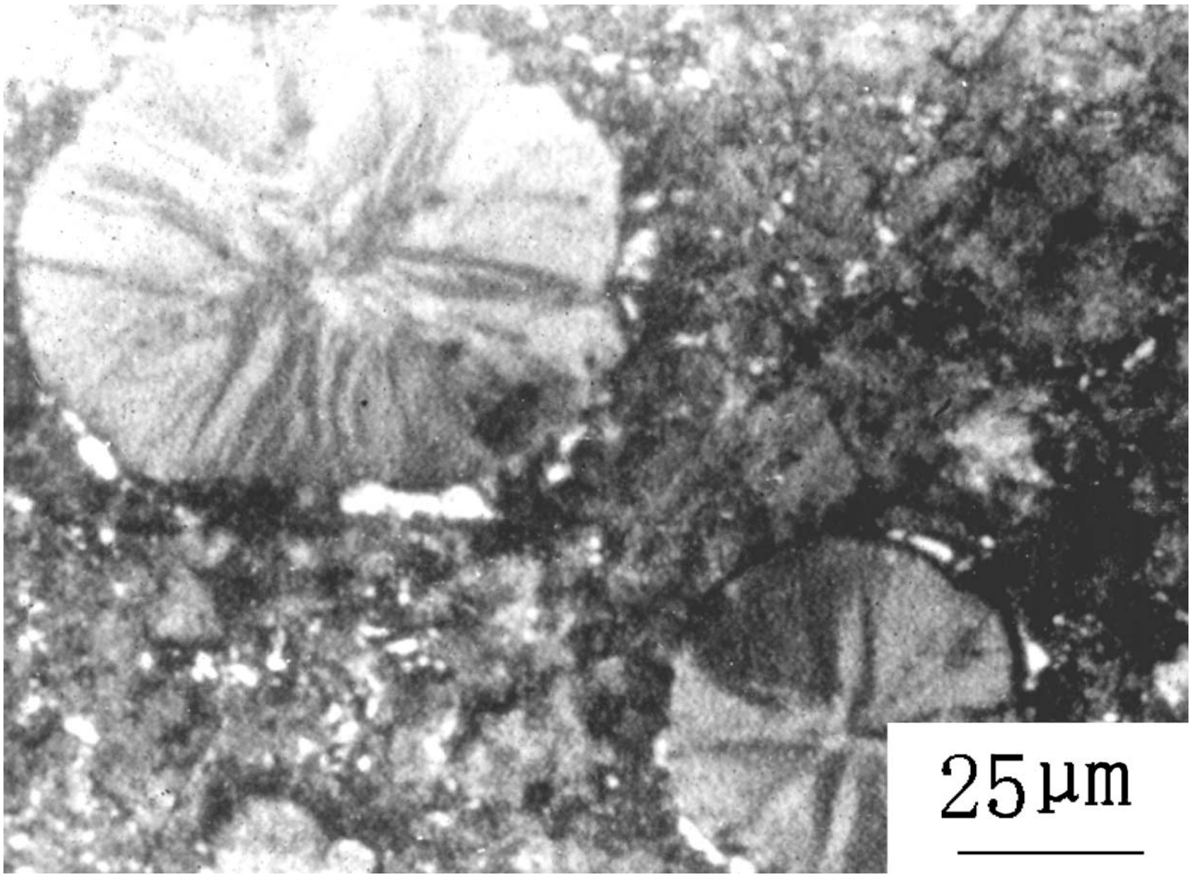


Figure 4 Microstructure of the austenite transformation zone.

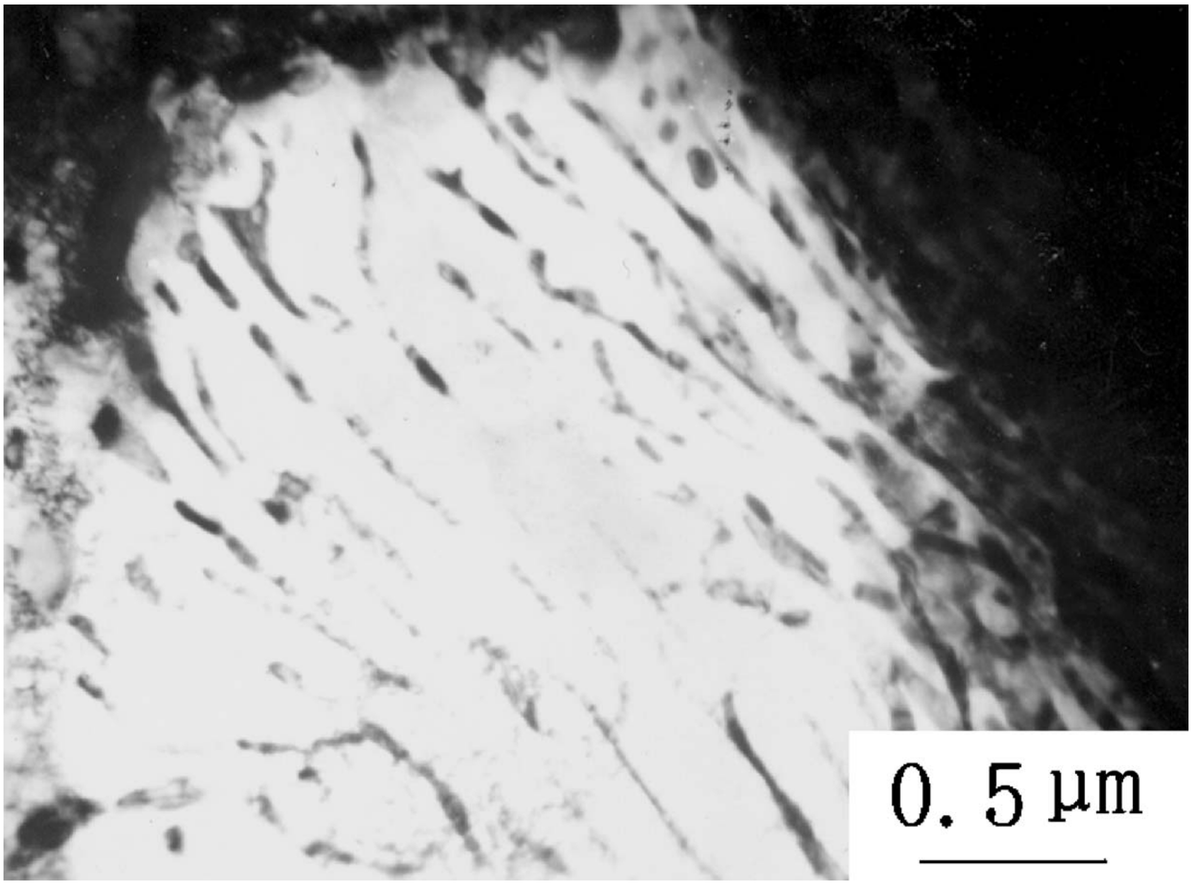


Figure 5 Pearlite microstructure in the austenite transformation zone.

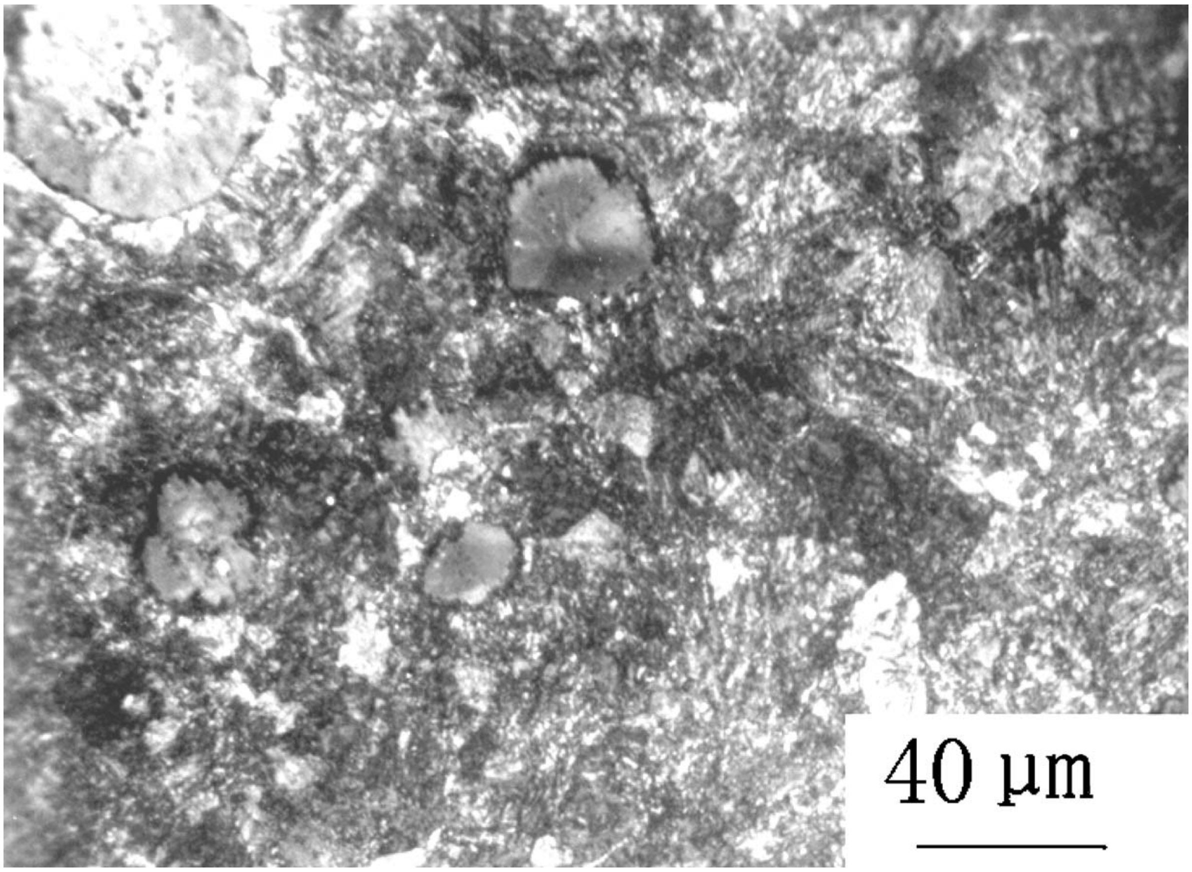
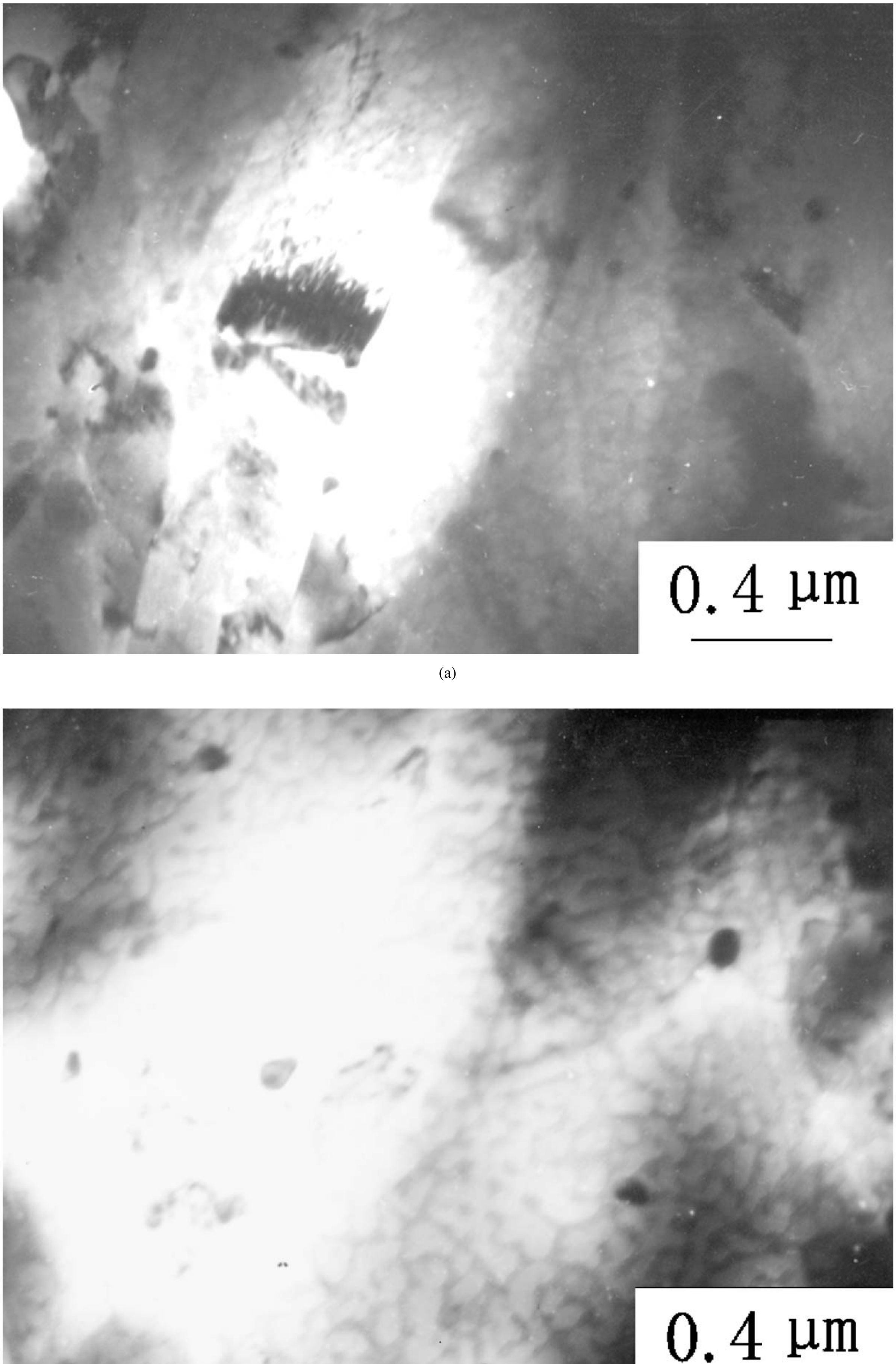


Figure 6 Microstructure of the repeated transformation zone.



(a)

(b)

Figure 7 The change of the bainite plates at high temperature: (a) at 800 °C and (b) at 850 °C.

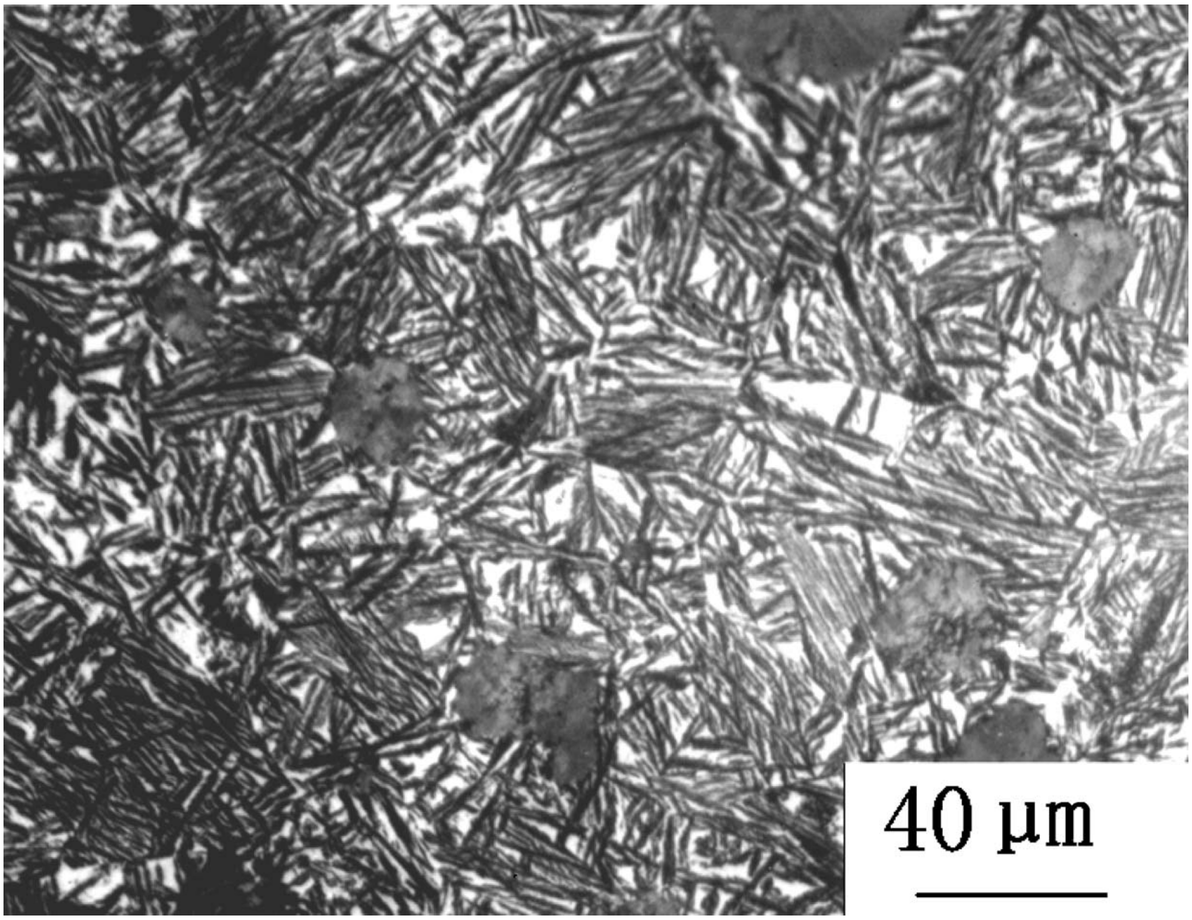


Figure 8 Microstructure of ADI base metal.

uniform austenite matrix, see Fig. 7b. The room matrix microstructure in the zone will consist of pearlite plus bainite, and it can be seen from the Fig. 6 that the contours of the bainite plates have become unclear. Fig. 8 shows the microstructure of the base metal. The maximum heating temperature in this zone is lower than the lower limit of the eutectoid temperature. No obvious change can be seen in the microstructure of the zone.

The specimens for tensile test were taken across the joint. It has been found that the specimens fractured in the austenite transformation zone. The ultimate strength of the joint was of 695 MPa and the elongation of the whole joint was2%.

References

1. E. DORAZIL, Czechoslovak Patent No. 157850 (July 20, 1971).
2. D. Y. LI, Z. F. ZHOU and C. J. SHAO, *AFS Transactions.* **98**(38) (1998) 59.
3. *Idem., AFS Transactions* **98**(49) (1998) 77.
4. DEYUAN LI, ZHENFENG ZHOU and DAQIAN SUN, *J. Mater. Sci. Technol.* **14** (1998) 147.
5. Z. F. ZHOU and D. Y. LI, *Trans. China Weld. Inst.* **16** (1995) 125.

Received 21 April
and accepted 28 May 2004