Weld metal impact toughness of electron beam welded 9% Ni steel

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9% Ni steel was electron beam welded and the impact toughness of its weld metal was investigated. The improvement of weld metal toughness was studied by an increase of Ni content in the weld metal and its mechanism was discussed. The weld metal impact toughness was as low as 25–55 J at −196°C. However, it increased remarkably by an increase of Ni and showed 118 J at the same temperature when Ni content was 16.6%. As Ni lowers the martensite start temperature, martensite formed in weld metal with a high Ni content has more chance of auto-tempering because of its slow cooling rate at a low temperature range. Therefore, the improvement is believed to be due to the formation of auto-tempered martensite and retained austenite during the cooling cycle after welding

1. Introduction

As 9% Ni steel has shown high toughness and strength at temperatures as low as −196°C, it has been used extensively as a material for the storage and transportation of natural gas. For welding of 9% Ni steel, arc welding processes such as shielded metal arc (SMA), gas metal arc (GMA) and submerged arc (SA) welding processes are the most widely used so far. However, as all these arc welding processes use high Ni-base welding consumables, the weld metal often results in solidification cracking or strength loss due to dilution [1]. Compared to the arc welding processes, the electron beam (EB) welding process, however, has many unique advantages in welding of 9% Ni steel. As it uses no welding consumables, the weld metal shows none of the welding defects mentioned above. Moreover, as it produces deep penetration and a narrow fusion zone, and deformations such as shrinkage and angular distortion are very small, even thick plates can be welded satisfactorily and economically. In spite of these advantages, the EB welding process has been limited in its application because the process was limited strictly to operation in a high vacuum chamber. But the development of local chamber or non-vacuum welding techniques in recent years has given more serious consideration to the application of the process for the welding of 9% Ni steel [2].

In this study, 9% Ni steel was EB welded and the impact toughness of weld metal at −196 °C was investigated and compared with those obtained in the arc welding processes. The improvement of weld metal toughness was also studied by the increase of Ni content in weld metal and its mechanism was discussed.

2. Experimental procedure

The chemical composition and mechanical properties of the 9% Ni steel used is shown in Table I. The steel is 23 mm in thickness and manufactured by a quenching-lamellarizing-tempering process. Using a square-groove joint, EB welding was performed with various accelerating voltage (V) and beam current (I) in high vacuum of 1.6×10^{-2} Pa with a constant welding speed (v) of 500 mm/min. The active parameter, distance between focal lens and workpiece-to-distance between focal lens and focus ratio, was maintained as a unit throughout the whole experiments. After welding, the penetration depth and weld metal width were measured using a profile projector. Chary impact test specimens with standard 2 mm V-notch at the center of weld metal was machined and tested at −196°C. The notch direction was perpendicular to the weld line. To change the Ni content in weld metal, pure Ni wires were inserted in the holes which were drilled at the faying surface of square-groove joint. As shown later, this technique results in uniform Ni content in weld metal.

The weld metal microstructure was examined using optical microscopy (OM) and transmission electron microscopy (TEM). Thin foil specimens for TEM were obtained using a jet electropolisher and an alchol-8% perchloric acid electrolyte. The thin foils were examined in a JEOL 200CX TEM at 200 kV. The amount

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TABLE I Chemical composition and mechical properties of 9% Ni steel used

chemical composition (wt. %)							mechanical properties			
C	Si	Mn	P	S	Ni	Al	YP (MPa)	TS (MPa)	El (%)	$_{v}E_{-196}$ (J)
0.07	0.25	0.26	0.004	0.001	9.2	0.03	671	729	30	220

of retained austenite in weld metal was also investigated by Fe^{57} Mössbauer spectroscopy. The gamma ray source is a radioactive isotope Co^{57} and source drive unit is EG&G Model 556. The specimen for the measurement was electropolished to minimize the effect of deformed layer.

3. Results and discussion

To determine an optimum welding condition for full penetration of 23 mm-thickness plate first, variations of penetration depth with V and I were measured. As shown in Fig. 1, the penetration depth was increased rapidly with an increase of I in the whole current range investigated in 120 and 150 kV and showed full penetration at higher than 50 mA. However, it had never showed full penetration at any current investigated in 60 and 90 kV. Therefore, V and I were maintained above 120 kV and 50 mA, respectively in order to obtain full penetration. Charpy impact test specimens were machined and tested at −196°C after welding with a full penetration condition. Impact toughness, however, showed large scatter of 25–180 J. Moreover, the fracture path of the specimens was not limited in weld

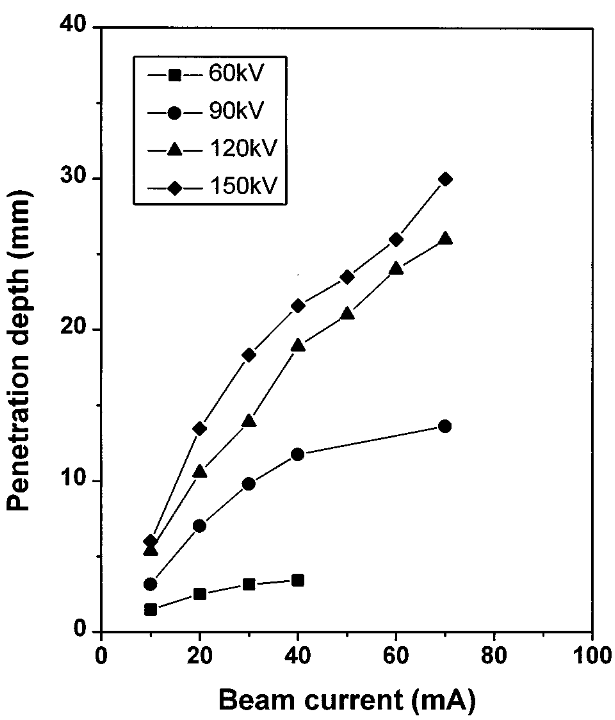

Figure 1 Variation of the weld metal penetration depth with beam current and accelerating voltage.

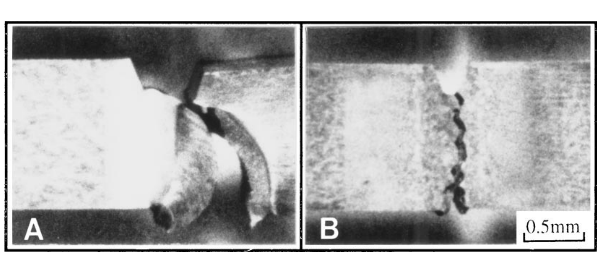

Figure 2 Fracture appearance of impact test specimens: (A) 120 kV-50 mA-500 mm/min; (B) 120 kV-30 mA-100 mm/min.

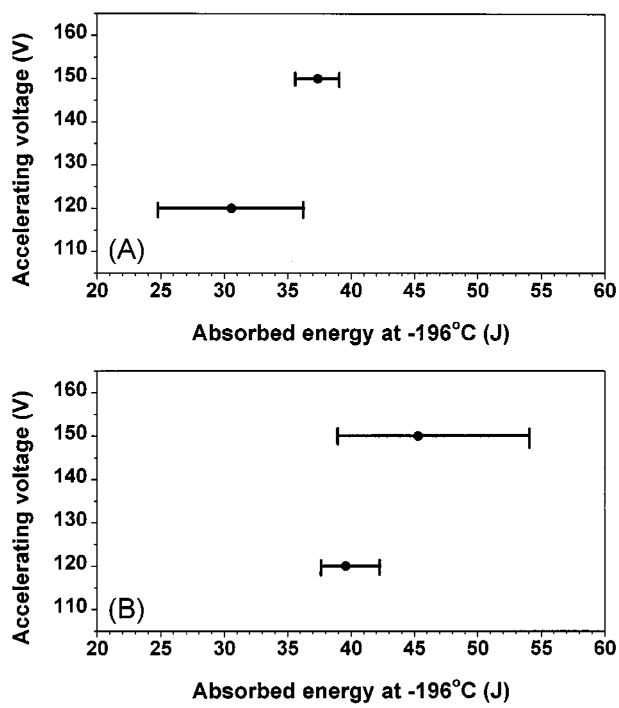

Figure 3 Impact toughness of weld metal (A) in high vacuum and (B) low vacuum welding.

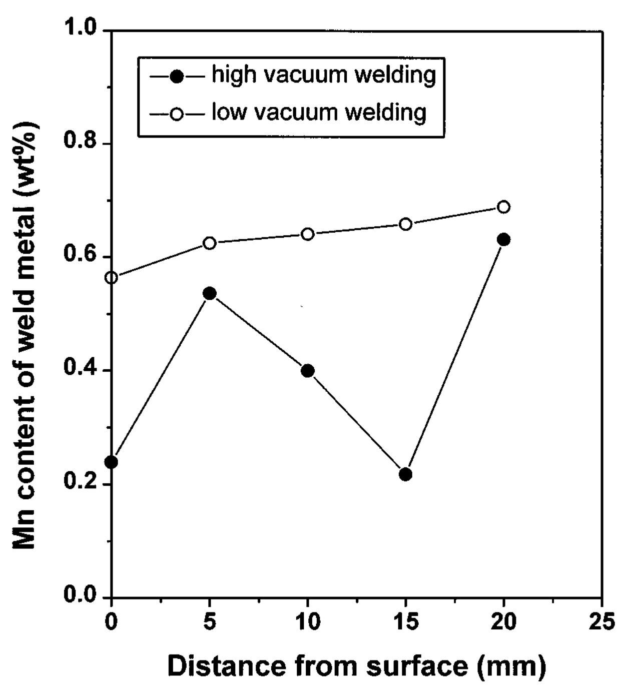

Figure 4 Mn content of weld metal in high and low vacuum welding.

metal, but propagated to base metal as shown in Fig. 2A. This is because the weld metal width is as small as 1.5–2.1 mm and weld metal hardness (350–370VHN) is much higher than base metal hardness (230VHN). Hence I and v were changed to increase the weld metal width. When I and v were decreased to 30 mA and 100 mm/min, respectively, weld metal width was increased to 2.5–2.9 mm with full penetration. The fracture path of the specimens was limited only in weld metal at this welding condition as shown in Fig. 2B and thus weld metal toughness was measured properly.

Fig. 3 shows the impact toughness of weld metal. In addition to high vacuum, 1.6×10^{-2} Pa, low vacuum, 1.6 Pa, was also used to study the effect of vacuum conditions on the impact toughness of weld metal. High vacuum welding (A) shows slightly lower impact toughness than low vacuum welding (B). This is because Mn content in weld metal is lower in high vacuum welding due to the evaporation loss of Mn during welding. Mn content of both weld metals were determined by electron microprobe analysis and compared. As shown in Fig. 4, Mn content in low vacuum welding is relatively uniform along through-thickness direction of weld metal and almost same as base metal content 0.7%. In high vacuum welding, however, it is not uniform and shows lower content than base metal due to the Mn evaporation. This is confirmed by Matsuta's result [3]. He reported that about 30% of base metal Mn was lost in high vacuum welding.

Compared to the results obtained in arc welding processes, the impact toughness in this experiment, 25–55 J (Fig. 3), is very low. For example, Choo *et al.* [4] reported that impact toughness of SMAW and SAW weld metals showed 70–120 J at −196°C. The improvement of impact toughness of EB weld metal was exploited by an increase of Ni content in weld metal. Pure Ni wires were inserted at the faying surface in square-groove joint as mentioned before. The welding condition was 150 kV-30 mA-100 mm/min, and low vacuum was used. The variation of Ni content in the weld metal after welding was determined by electron microprobe analysis. Fig. 5 shows that as the number of Ni wire was increased from one to five, average Ni content in weld metal was increased from 10.4% to 16.6%. It also shows that reasonably uniform Ni content is obtained by this technique. Fig. 6 shows the comparison of impact test results between weld metal with and without of Ni wires. At −196°C, weld metal with five Ni wires shows 118 J, while weld metal without Ni wires shows only 45 J. The impact toughness at −196°C was improved remarkably by an increase of Ni content.

Fig. 7A–E show optical microstructures of weld metal with different numbers of Ni wires. All weld metals show a lath martensitic microstructure. However, it contains a massive second phase indicated by the arrow and its amount increases with the increase of Ni wires. A typical TEM microstructure of weld metal, (F), shows that the massive second phase has very fine precipitates. From the TEM micrographs and selected area diffraction pattern (SADP) of the precipitates shown in Fig. 8, the precipitates are ε-carbides which are known to form at 100–200°C tempering temperature [5]. It also shows that its close-packed plane (002) is parallel to the close-packed plane of matrix (011) and its growing direction is coincident with the close-packed direction of matrix [111]. Based on this result, it is believed that the massive second phase is auto-tempered martensite with ε-carbides in it. As both the martensite start transformation (M_s) and finish temperature (M_f) are lowered with an increase of Ni content, the weld metal with high Ni content stands a good chance of tempering because of its slow cooling rate at low temperature range. The effect of a low M_s and M_f in weld metal with a high Ni content is also confirmed by

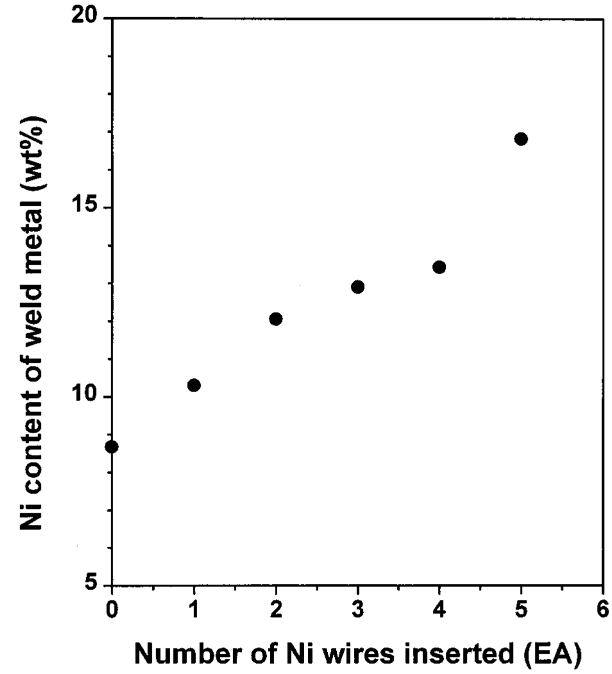

Figure 5 Variation of Ni content in weld metal with the number of Ni wires inserted.

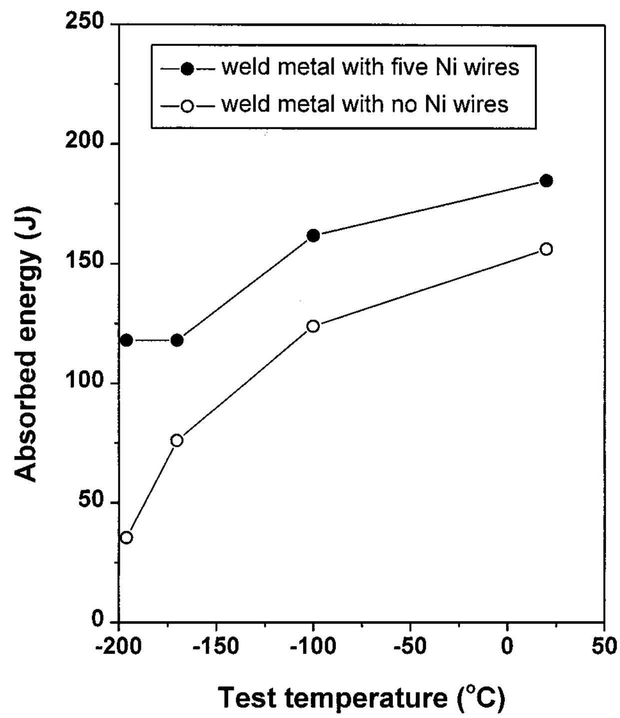

Figure 6 Comparison of impact toughness between weld metal with five Ni wires and no wires.

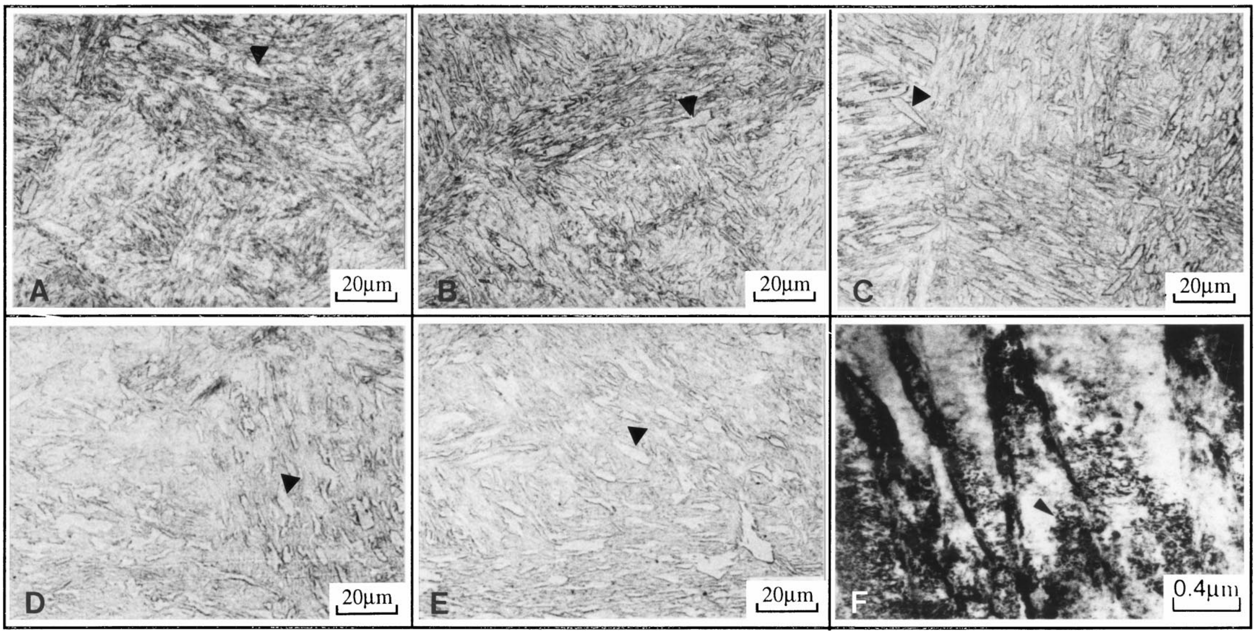

Figure 7 (A–E) Optical microstructural changes of weld metal with Ni wires and (F) a typical TEM microstructure of weld metal: (A) one; (B) two; (C) three; (D) four; (E) five Ni wires.

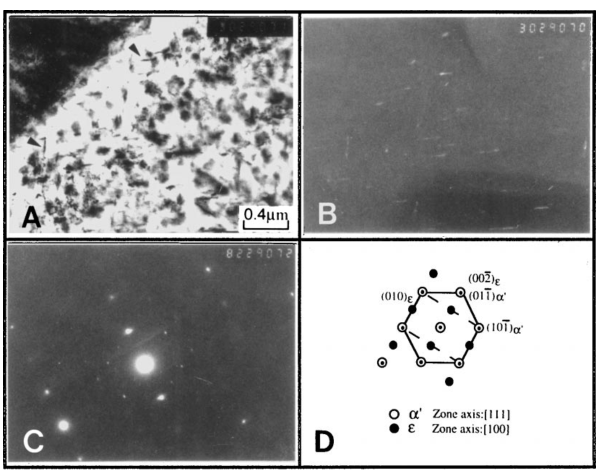

Figure 8 TEM micrographs of the precipitates in massive second phase: (A) bright field; (B) dark field; (C) and (D) SADP.

the presence of more retained austenite in weld metal. The result of Mössbauer spectroscopy showed that the amount of retained austenite in weld metal with five Ni wires is 4.8 at.%, while it was only 2.7 at.% in weld metal without Ni wires. Therefore, the improvement of impact toughness of weld metal is ascribed to the formation of auto-tempered martensite during the welding cooling cycle and an increase of retained austenite. Several explanations have been given for the beneficial effect of retained austenite on toughness. According to Nostrom [6], it scavenges detrimental carbon elements and thus increases toughness of the ferrite, and austenite itself absorbs impact shock more easily and blunts crack propagation effectively.

4. Conclusions

The weld metal impact toughness of electron beam welded 9% Ni steel was as low as 25–55 J at −196°C. However, it increased remarkably with an increase of Ni content. Weld metal with 16.6% Ni showed 118 J at the same temperature. As Ni lowers the martensite start transformation, martensite formed in weld metal with a high Ni content has more chance of auto-tempering because of its slow cooling rate at a low temperature range. Mössbauer spectroscopy showed that the amount of retained austenite in weld metal was increased with an increase of the Ni content. Therefore, the improvement is believed to be due to the formation of auto-tempered martensite and retained austenite during the welding cooling cycle.

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