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Microstructure and Mechanical Properties of 9Cr-1Mo Steel Weld Fusion Zones as a Function of Weld Metal Composition

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Modified 9Cr-1Mo steel, designated as P91, is widely used in the construction of power plants and other sectors involving temperatures higher than 500 °C. Although the creep strength is the prime consideration for elevated temperature applications, notch toughness is also important, especially for welded components, as it is essential to meet the pressure test and other requirements at room temperature. P91 steel weld fusion zone toughness depends on factors such as welding process, chemical composition, and flux composition. Niobium and vanadium are the main alloying elements that significantly influence the toughness as well as creep strength. In the current work, weld metals were produced with varying amounts of niobium and vanadium by dissimilar joints involving P9 and P91 base metals as well as filler materials. Microstructural studies and Charpy V-notch impact testing were carried out on welds to understand the factors influencing toughness. Based on the results, it can be concluded that by reducing vanadium and niobium weld metal toughness can be improved.

Keywords 9Cr-1Mo steel, chemical composition, hardness, microstructure, toughness, weld metal

1. Introduction

The need to reduce fuel costs as well as environmental pollution from fossil fuels by significantly decreasing carbon dioxide emissions from power-generating plants has led to efforts to increase the thermal efficiency of power plants (Ref 1). This necessitates the use of steels with improved high-temperature properties. The development of Cr-Mo ferritic steels, ranging from 1%Cr-0.5%Mo (P11) to 12%Cr-1%Mo (P122), is of great interest in this regard. Among the Cr-Mo ferritic steels, 'modified' 9Cr-1Mo (P91) steel developed by the Oak Ridge National Laboratory (ORNL) in USA by increasing the nitrogen content of the basic 9Cr-1Mo (P9) composition and adding small amounts of vanadium (V) and niobium (Nb) is being widely used today. Although the P91 steel is intended primarily for elevated temperature applications, it is essential that weld metal toughness is adequate to meet pressure test and other requirements at room temperature. A minimum average of 47 J for the tempered weld metal (minimum single value of 38 J) at room temperature has to be ensured as per the European specification EN 1599:1997.

It has been shown earlier that reduction in Nb, V, and Si contents improves toughness (Ref 2), while increase in nickel content is beneficial (Ref 2, 3). But a lower limit of Nb content is essential for satisfactory creep resistance. Onizawa et al. showed that the impact properties of welds degrade with the increase in V and Nb contents (Ref 4). The addition of a controlled level of nickel is beneficial since it lowers the Ac_1 temperature bringing it closer to the PWHT temperature thereby improving the response to tempering and reduces the tendency for residual δ ferrite. Although there are only limited studies on the effect of δ ferrite on the weld metal properties, it is believed that it has a detrimental effect on both creep resistance and toughness (Ref 5, 6).

The present study deals with the effect of composition on the weld fusion zone toughness of 9Cr-1Mo steel shielded metal arc (SMA) weld metals, especially Nb and V. Weld metals have been produced using combinations of P91 and P9 (standard 9Cr-1Mo steel) base and filler materials are subjected to a PWHT at 760 °C for 2 h. Charpy V-notch impact testing and microstructural studies were carried out on welds to understand the factors influencing toughness.

2. Experimental

Standard 9Cr-1Mo steel (P9) in the normalized (960 °C for 0.3 h) and tempered condition (760 °C for 1 h) and modified 9Cr-1Mo steel (P91) plates in the normalized (1080 °C for 1 h) and tempered (760 °C for 2 h) condition were used for welding trials. The plates of size 220 × 110 × 12 mm, were butt welded (single V with included groove angle 60, root face 1.6 mm and root gap 2.5 mm) using 3.15 mm diameter filler material. Table 1 shows the composition of the base materials and diluted weld metals. The study involved four weld joint

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configurations, designated as A, B, C, and D, to produce different concentrations of Nb and V in weld metals and the configuration is as follows:

A: P9 (base metal) – P9 (filler) – P9 (base metal)
B: P9 (base metal) – P91 (filler) – P9 (base metal)
C: P91 (base metal) – P9 (filler) – P91 (base metal)
D: P91 (base metal) – P91 (filler) – P91 (base metal)

Weld pads were prepared using heat input of 1.64 kJ/mm with preheat temperature of 200 °C and interpass temperature of 250 °C maintained during welding. The electrodes were baked in an oven at 250 °C for 2 h before welding. Defect-free weldments were subjected to postweld heat treatment at 760 °C for a period of 2 h after radiography inspection.

Light optical microscopy of the weld fusion zones was carried out using an etchant consisting of 10 g $FeCl_3$, 30 mL HCl, and 120 mL H_2O. Thin slices of 1 mm thickness lying in the fusion zone were cut and prepared using standard procedures for TEM studies. Final thinning of samples for TEM studies was done using the electrolytic double jet technique, with an electrolyte having a mixture of 80% methanol and 20% perchloric acid. Scanning electron microscopy (SEM) on plane, polished specimens was also done. Hardness surveys were made across the welds with a 10 kg load. Fusion zone toughness was measured using Charpy testing at room temperature (30 °C) as well as at 0 and −30 °C on transverse specimens with a notch orientation such that the crack propagates in the weld metal along the welding direction.

3. Results and Discussion

3.1 Chemical Composition

The chemical composition of diluted weld metals is listed in Table 1. From the weld metal compositions, it may be observed that as expected the V and/or Nb contents are minimum in weld metal A (0.03/0.03), slightly higher in weld metal C (0.05/0.03), and maximum in the weld metals B and D (0.15/0.06). It may be noted further that the carbon contents in the weld metals A and C are significantly lower than the carbon contents in the weld metals B and D. The oxygen content was high due to nature of acidic components in the flux system.

3.2 Microstructures

3.2.1 Base Materials. The microstructures of the base metals shown in Fig. 1(a) and (b) reveal tempered martensite. The TEM micrographs, Fig. 1(c) and (d), show the precipitates formed after tempering. Energy dispersive X-ray spectroscopy (EDS) analysis showed that both P9 and P91 have $M_{23}C_6$ precipitates, while P91 contained in addition particles that were rich in V and/or Nb.

3.2.2 As-Welded Condition. The optical micrographs of all the four weld metals A, B, C, and D are given in Fig. 2(a-d). Spherical microinclusions are clearly seen in the picture (Fig. 2a). They are mainly rich in silicon due to acidic nature of flux in the coating. During welding, the weld fusion zones solidify as ferrite, but pass through the austenite phase field on cooling; the austenite eventually transforms to martensite well before room temperature is reached. It is interesting to note that, although the structures seen in Fig. 2(a-d) are untempered martensite, some precipitates are observed (in addition to inclusions) both on the prior austenite grain boundaries and along the lath boundaries. This is obviously a result of the low carbon content in these weld metals, which implies a relatively high M_s temperature (420 °C) that causes a certain amount of auto-tempering.

Figure 3(a-d) represents transmission electron micrographs in the as-welded condition. The lath martensitic structure is clearly revealed in Fig. 3(a) (taken from weld metal B). The presence of some needle-like precipitates can be observed in Fig. 2(b), also from weld metal B. EDS analysis of precipitate has shown that they are rich in iron and chromium. The weld metal C produced with the P9 electrode was found to contain, even in the as-welded condition, a precipitate that was rich in Nb, see Fig. 3(c) and (d). The presence of Nb-rich precipitate in weld metal C, which is made using P9 electrode, can be attributed to dilution from the P91 base metal. All these precipitates were apparently formed during auto-tempering as discussed earlier.

3.2.3 Postweld Heat-Treated Condition. During postweld heat treatment (760 °C for 2 h), the martensite gets tempered, carbides and carbonitrides precipitate out during tempering. This can be noticed in Fig. 4(a-d), which, however, do not illustrate any significant difference in the degree of precipitation between the weld metals A and C made with P9 electrodes and the weld metals B and D produced with P91 electrodes. The greater extent of precipitation in B and D during postweld heat treatment can be seen more clearly in the scanning electron micrographs shown in Fig. 5(a-d).

Transmission electron microscopy of samples in the postweld heat-treated condition showed that the lath structure had broken up and subgrains had formed; see for example Fig. 6(a) taken from weld metal C. Most of the precipitates formed on tempering were rich in iron, chromium, and molybdenum and were presumably of the $M_{23}C_6$ type. These were often found on both prior austenite and subgrain boundaries. Figure 6(b) shows the precipitate decorating the subgrain boundaries. In specimens from weld metal B (Fig. 6c) and weld metal D (Fig. 6d), typical cuboidal particles that were rich in V and Nb were observed, as revealed in the EDS spectrum given in Fig. 6(e).

Table 1 Chemical composition of base materials and diluted weld metals (wt.%)

Material	C	Si	Mn	Cr	Mo	V	Nb	Ni	Oxygen, ppm
P9 base metal	0.07	0.26	0.35	8.24	0.95	...	...	...	...
P91 base metal	0.08	0.5	0.39	9.4	1.0	0.25	0.09	0.13	...
Weld A	0.06	0.45	0.45	9.0	0.80	0.03	0.03	0.15	811
Weld B	0.09	0.35	0.50	9.0	0.95	0.15	0.06	0.55	652
Weld C	0.06	0.50	0.43	9.5	0.82	0.05	0.03	0.15	792
Weld D	0.09	0.30	0.50	9.0	0.95	0.15	0.06	0.55	692

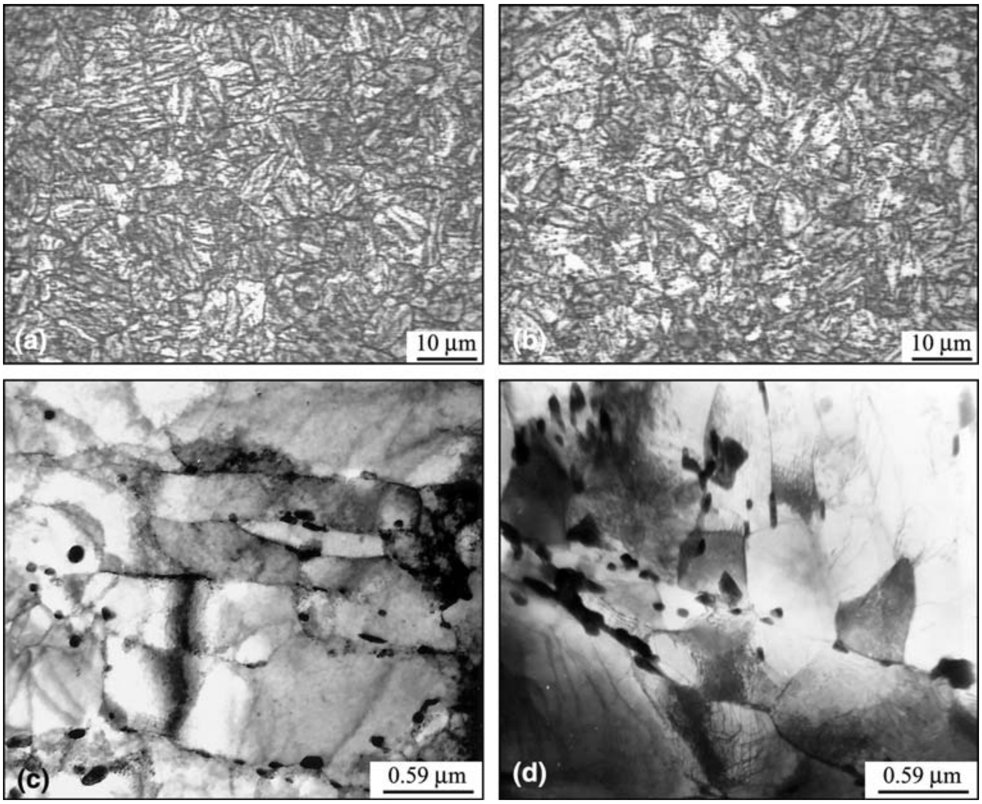

Fig. 1 P9 and P91 steels in normalized and tempered condition. Optical images: (a) P9 and (b) P91; TEM images: (c) P9 and (d) P91

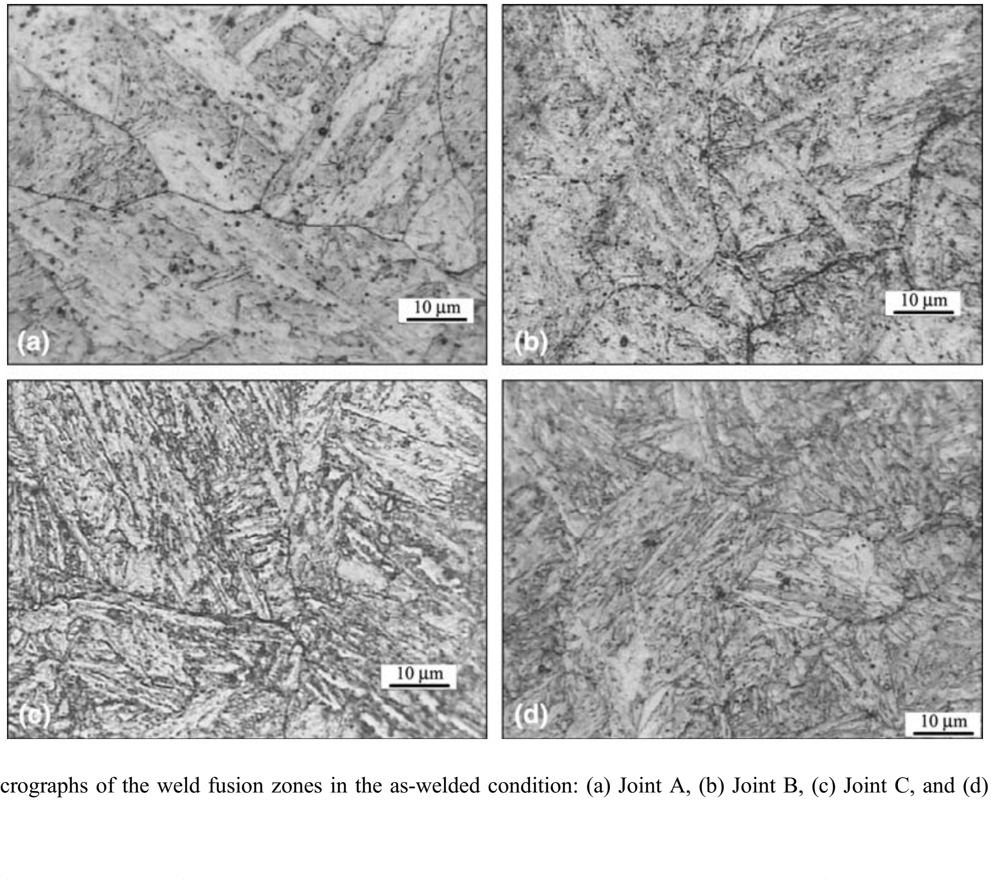

Fig. 2 Optical micrographs of the weld fusion zones in the as-welded condition: (a) Joint A, (b) Joint B, (c) Joint C, and (d) Joint D

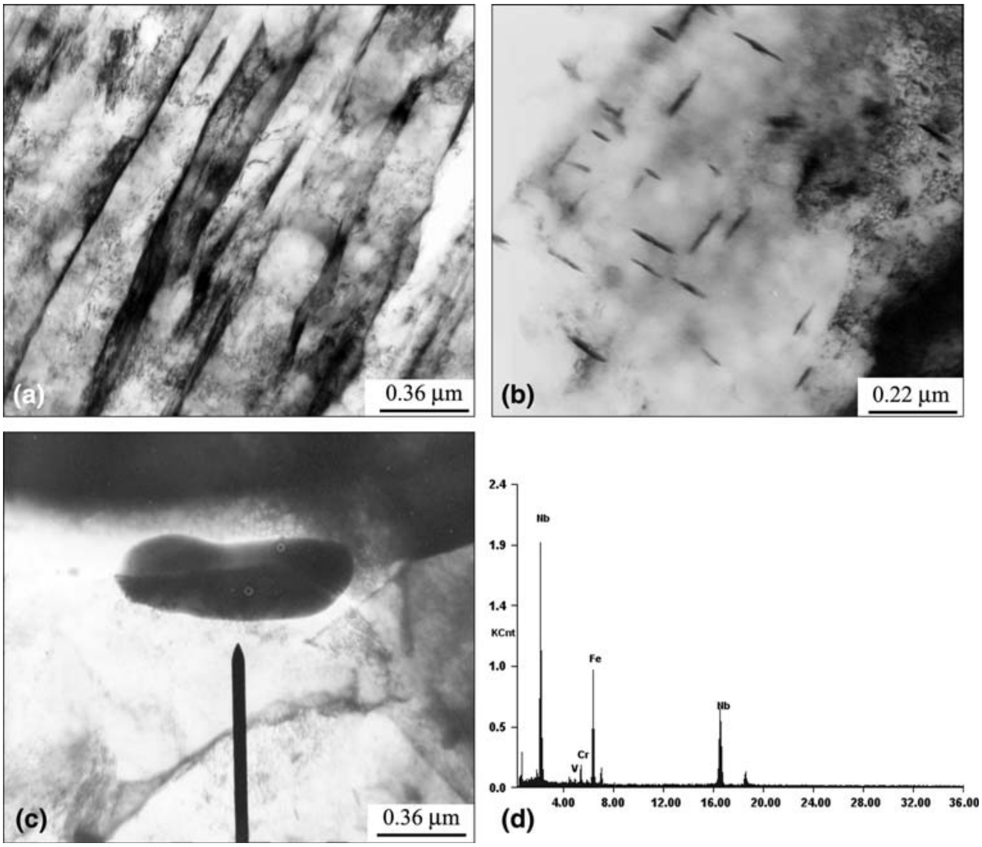

Fig. 3 Transmission electron micrographs of weld fusion zones in the as-welded condition: (a) weld metal B, (b) weld metal B, (c) weld metal C, and (d) EDS spectra corresponding to particle indicated in Fig. 3(c)

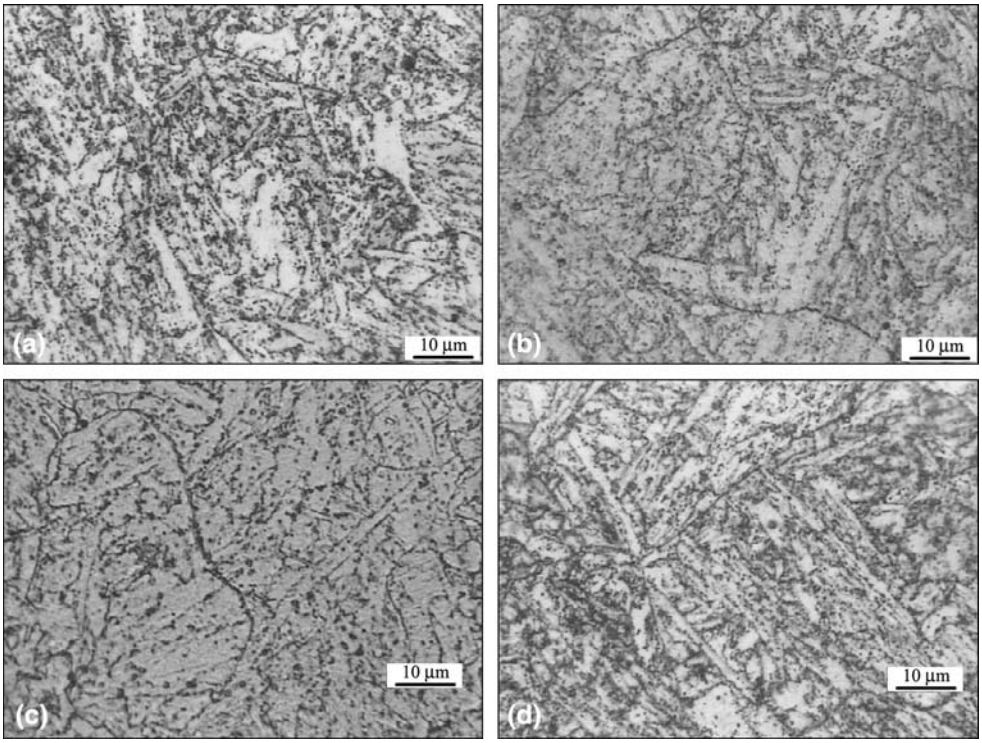

Fig. 4 Optical micrographs of the weld fusion zones after PWHT condition (760 °C for 2 h): (a) Joint A, (b) Joint B, (c) Joint C, and (d) Joint D

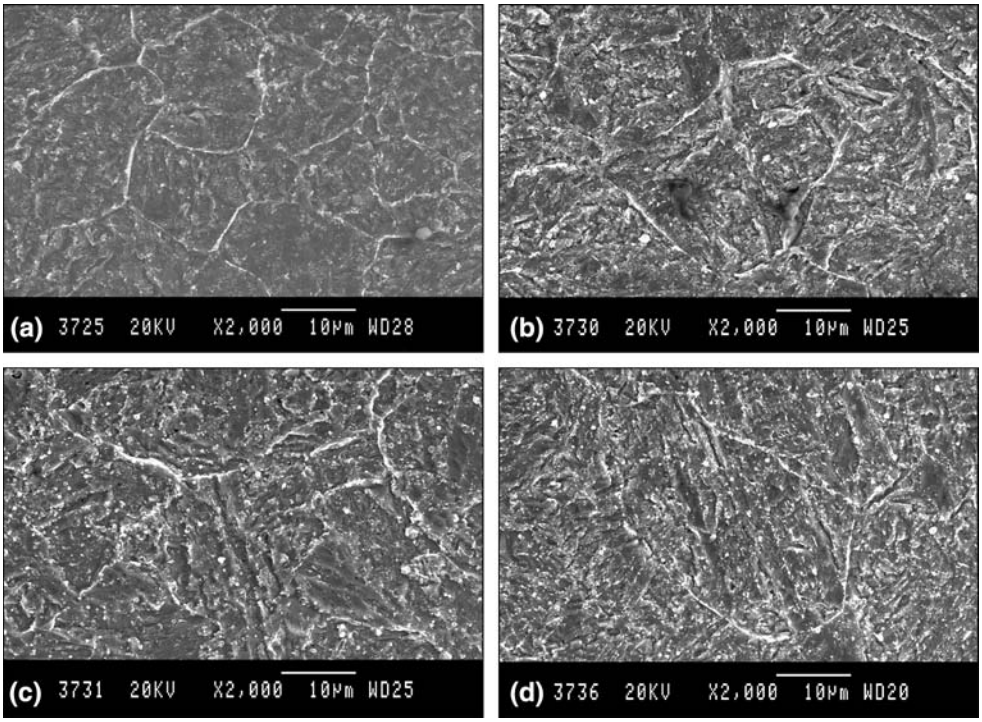

Fig. 5 Scanning electron micrographs of the weld fusion zones after PWHT condition (760 °C for 2 h): (a) Joint A, (b) Joint B, (c) Joint C, and (d) Joint D

3.3 Hardness

The hardness of the weld metal in as-welded condition and after postweld heat-treatment condition is evaluated using Vickers hardness at a load of 10 kg. High hardness above 400 VHN in the as-welded condition is attributed to the martensitic microstructure. However, the weld metals B and D exhibit slightly higher hardness (507 and 452 HV, respectively) than the weld metals A and C (421 and 422 HV, respectively), which may be attributed to the higher carbon content in B and D than in A and C. A less significant contribution could also result from the slightly higher alloy contents in the weld metals B and D (Mo, Ni, V, and Nb). The tempering of the as-welded martensite during postweld heat treatment results in a considerable lowering in hardness of the welds. The hardness of tempered weld metals B and D (274 and 275 HV, respectively) are higher than A and C (243 and 250 HV, respectively) to be attributed to the additional presence of Nb- and V-rich precipitates in B and D.

3.4 Notch Toughness

The Charpy impact toughness test data for the welded joints are shown in Fig. 7 for the three test temperatures, viz., room temperature, 0 and −30 °C. Clearly, the toughness values appear to be a function of the V and Nb contents of the weld metals, with the room temperature toughness being highest for the weld metal A (65.3 J) and least for B and D (39.7 and 43.3 J, respectively), with C exhibiting an intermediate value (52.3 J). At −30 °C, toughness reduced to ~15 J for all the weld metals.

The results clearly reveal the effect of Nb on impact toughness of the weld metal. The 9Cr-1Mo weld metal of joint A, in spite of the high oxygen content (Table 1), exhibited higher toughness than the modified 9Cr-1Mo (P91) weld metal of joint D. Normally higher oxygen content indicates higher inclusion content and lower toughness. On that basis, the weld metal of joint A can have lower toughness than weld metal D. Since, it is not so, the low toughness of weld metal of joint D can be clearly attributed to the presence of higher amount of Nb, V, and C than in the weld metal A. In the case of weld metal of joint C, the weld metal of P9 consumable is diluted with the molten metal of the P91 base metal and this resulted in some decrease in toughness. This is also supported by Nb-rich precipitates observed in the weld metal of joint C (Fig. 3 c, d). In contrast, in the case of weld metal of joint B, dilution from base metal was not sufficient to bring in any improvement in toughness. For all the weld metals, toughness decreased drastically with temperature and this is expected for ferritic steel weld metals.

4. Summary

Weld metals of joint A and C which are produced using P9 consumable having lower Nb and V content exhibited better toughness (above 47 J) than B and D (below 47 J), clearly revealing adverse effect of Nb and V on toughness. This is due to higher amount of V and Nb in weld metals of joint B and D than A and C. Dissimilar weld joints of P9 and P91 steels is another option that is capable of achieving toughness requirement of minimum 47 J during pressure testing or start-up of power plant components.

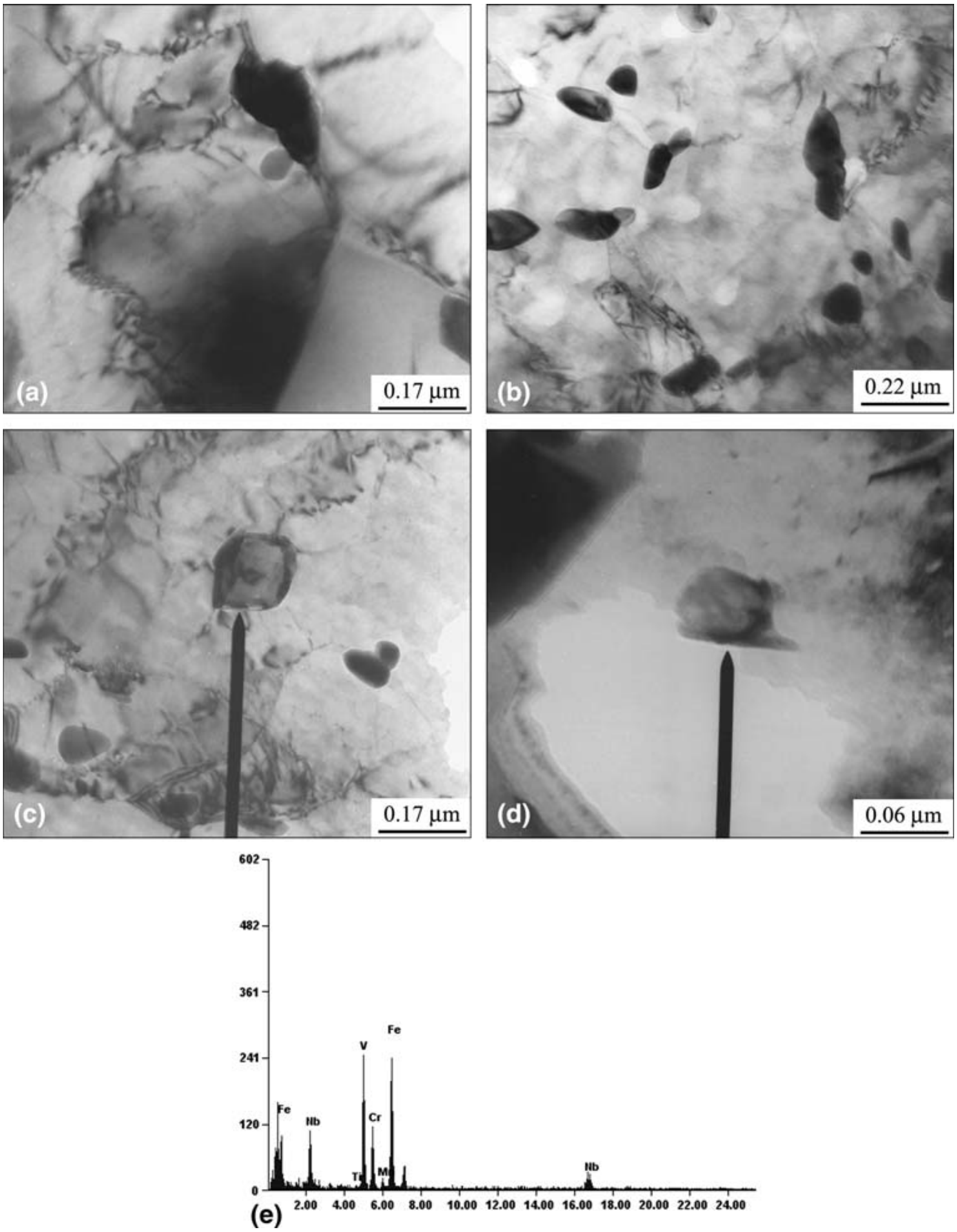

Fig. 6 Transmission electron micrographs of weld fusion zones after PWHT condition (760 °C for 2 h): (a) weld metal C, (b) weld metal A, (c) weld metal B, (d) weld metal D, and (e) EDS spectra corresponding to particle indicated in Fig. 6(d)

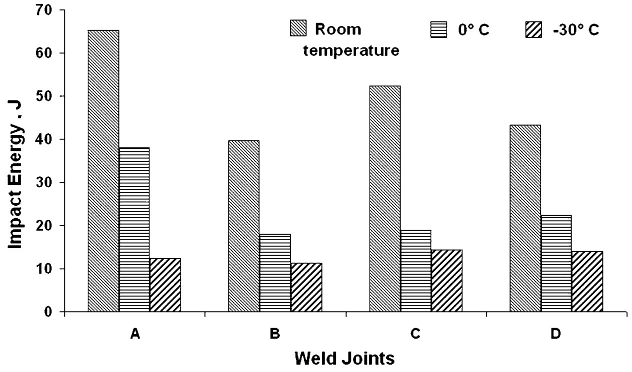

Fig. 7 Charpy impact values for the weld metals after PWHT at 760 °C for 2 h

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