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Microstructure and creep properties of high Cr resisting weld metal alloyed with Co*

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Abstract: A 9% Cr ferritic steel weld metal containing 1% Co, partially substituted for nickel, was prepared by submerged arc welding (SAW) processing. The microstructure and creep properties of the weld metal were investigated. The microstructure exhibited a fully tempered martensitic structure free of δ-ferrite. The creep properties of the obtained weld metal were inferior to those of the P92 base metal at 600 and 650 °C. The values of A and n for weld metal in the Norton power law constitution at 650 °C are 1.1×10^{-21} and 8.1, respectively.

Key words: 9Cr steels, Weld metal, Microstructure, Creep properties
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1 Introduction

High Cr ferritic heat resisting steels are regarded as the best potential material for ultra-supercritical (USC) power plants (Masuyama, 2001; Kern *et al.*, 2002). In the new generation of ferritic chromium steels, tungsten has been added to improve creep rupture strength. The newly developed typical steels, ASME-P92 (9Cr-0.5Mo-1.8W-VNb), ASME-T/P911 (European E911) (X11CrMoWVNb9-1-1), and ASME-P122 (11Cr-0.4Mo-2W-CuVNb) (Bendick *et al.*, 1999; Masuyama, 2002; Vaillant *et al.*, 2008) grades of steels have been widely used. It is of great importance that matching filler metals are developed simultaneously to base metals (Baune *et al.*, 2006). Tungsten is a strong ferrite-stabilising element promoting the retention of δ-ferrite in the weld metal upon rapid cooling process. The detrimental effects of δ-ferrite on impact toughness and creep rupture properties of ferritic steels are well known (Kimura *et al.*, 2006). Therefore, weld metal development aims to eliminate retained δ-ferrite by modification of the chemical compositions of weld metal. The addition of nickel, an austenite-stabilising element, produces positive effects on the impact toughness of NF616 (P92) weld metal by suppressing the formation of δ-ferrite (Naoi *et al.*, 1995). However, as the nickel content increases, the Ac_1 transformation temperature falls below the post-welding heat treatment (PWHT) tempering considerably (Brühl, 1989). Thus, untempered martensite will appear in the weld metal, which is also detrimental to the toughness. The addition of cobalt has almost no influence on the transformation temperatures, but can also reduce retained δ-ferrite content effectively (Letofsky, 2001; Knežević *et al.*, 2008; Klotz *et al.*, 2008), which is likely to solve the problem. Previous studies have investigated the microstructure and creep properties of high Cr steels weld metal alloyed with about 1% nickel (Sireesha *et al.*, 2001; Santella *et al.*, 2003; Yamashita and Goto, 2003). However, little has been reported with regard to those of weld metals containing Co.

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In the current work, high Cr ferritic steel weld metal containing about 1% Co, partially substituted for nickel, was produced using the submerged arc welding (SAW) processing. The creep tests were performed at 600 and 650 °C to investigate the creep properties of weld metal, which was compared with those of P92 base metal.

2 Experimental

The pad weld metal was obtained by SAW using US-12CRSD filler metal and PF-200SD flux, both KOBE Steel products (Japan). The pad were made using 2.4 mm diameter wire deposited on a mild steel base 90 mm in thickness, which was built up with a minimum of 12 layers, about 37 mm in thickness. The welding conditions parameters used for preparing reducting the weld metal are given in Table 1. After completion, the pads were given a PWHT at 755 °C for 5 h. Specimens were machined from the upper layers to obtain the undiluted weld deposit.

Table 1 Welding parameters used for the production of the weld metal

Parameter	Value
Preheating temperature (°C)	200–250
Welding current (A)	370–390
Arc voltage (V)	30–34
Interpass temperature (°C)	200–300
Welding speed (mm/s)	6.1
Heat input (kJ/m)	600

The experiments were also conducted using P92 steel pipes with a dimension of Φ325 mm×71 mm produced by Vallourec & Mannesmann Tubes Industries (France and Germany), to investigate the difference in creep behaviour between the weld metal and the base metal. Heat treatment of P92 pipes is normalizing at (1060±20) °C and tempering at (765±15) °C. The chemical composition of the obtained weld metal and the P92 base metal are shown in Table 2.

Microstructural examination on the weld metal was carried out using both optical microscopy and transmission electron microscopy (TEM). The etchant Vilella's reagent was used to reveal the microstructure. TEM observations were carried out using thin foil specimens fetched from the weld metal. The creep round-bar specimens, with a gauge of Φ10 mm×100 mm, were exposed at 600 °C (150 MPa) and 650 °C (90, 100 and 110 MPa, respectively). Extensometers were attached to the specimen shoulders to measure the extension along the variation of time.

3 Results and discussion

3.1 Microstructure

The optical micrograph structure of the obtained weld metal is illustrated in Fig. 1. Because the pad was built up with multi-layer beads, weld metal exhibited the initial columnar grained microstructures, together with the coarse grained and fine grained microstructures formed by the weld thermal cycle of subsequent weld passes. A fully tempered martensitic structure free of δ-ferrite was observed in each zone of weld metal. The probability of δ-ferrite retention is a function of weld metal composition, depending on the relative amounts of ferrite and austenite stabilizers. The chromium equivalent empirical expressions (Sireesha *et al.*, 2001) have been suggested for estimating the tendency of ferrite retention:

$$\begin{aligned}\mathrm{Cr_{eq}}=&\%\mathrm{Cr}+6\%\mathrm{Si}+4\%\mathrm{Mo}+1.5\%\mathrm{W}+11\%\mathrm{V}\\&+5\%\mathrm{Nb}+8\%\mathrm{Ti}-40\%\mathrm{C}-2\%\mathrm{Mn}-4\%\mathrm{Ni}\\&-2\%\mathrm{Co}-30\%\mathrm{N}-\%\mathrm{Cu}.\end{aligned} \tag{1}$$

It has been suggested that the ferrite retention will appear in welds if $\mathrm{Cr_{eq}}>10$. $\mathrm{Cr_{eq}}$ (=8.8) for the tested weld metal is lower than 10. It can be seen that there is good agreement between the calculation and observation results, which indicates that the addition

Table 2 Chemical composition of the obtained weld metal and the P92 base metal (%, w/w)

Material	C	Si	Mn	Cr	Mo	Ni	W	V	Nb	Co	N	B
Filler metal	0.081	0.30	0.78	9.50	0.29	0.52	1.52	0.20	0.033	0.91	0.057	<0.0005
Weld metal	0.077	0.27	0.74	9.77	0.37	0.40	1.44	0.20	0.026	0.85	0.035	<0.0005
P92 base metal	0.12	0.21	0.43	8.84	0.50	0.16	1.67	0.21	0.067	–	0.042	<0.0005

of Co as an austenizing element is beneficial to suppression of the formation of δ-ferrite in the matrix of the weld metal. Addition of 1% Ni or 2% Co has been shown to be sufficient in eliminating retained δ-ferrite and improving impact toughness in modified 9Cr-1Mo combination steel with 1% W (Barnes and Abson, 2003). The results indicate that reducing the content of nickel to 0.4% as well as adding 1% Co could also eliminated retained δ-ferrite for 10Cr-0.5Mo-1.5W weld metal.

Fig. 2 shows the TEM micrograph of the weld metal, which exhibits the lath structure of the martensite with a high density of dislocation. The relative large particles, identified as $M_{23}C_6$ carbides, precipitate mainly along lath interfaces. Much finer particles are observed within the laths, identified as MX precipitates.

3.2 Creep curves

Some examples of creep curves measured in this study are shown in Fig. 3. The creep curves obtained consist of the well defined primary or transient creep range, where the creep rate decreases with increasing time, the long steady rate stage (or rather a minimum creep rate range), where the creep rate is constant, and the short tertiary (or acceleration creep region), where the creep rate increases with time. Being time-consuming and cost-intensive, some tests were interrupted before the tertiary stage. Hence, creep curves in Fig. 3 at 600 and 650 °C consist of only two stages without acceleration creep region.

Comparing the creep curves of the weld metal and P92 base metal, it can be seen that the former exhibits a higher secondary creep rate, which promotes the onset of the acceleration creep region, resulting in a shorter creep rupture time. The evidence mentioned above suggests that the creep properties of the obtained weld metal are inferior to those of the P92 base metal, which is likely due to the lower carbon content designed to minimize susceptibility of hot cracking in the weld metal.

3.3 Steady state creep rates

The variation in strain rate with stress during the steady-state for the weld metal and P92 base metal is illustrated in Fig. 4.

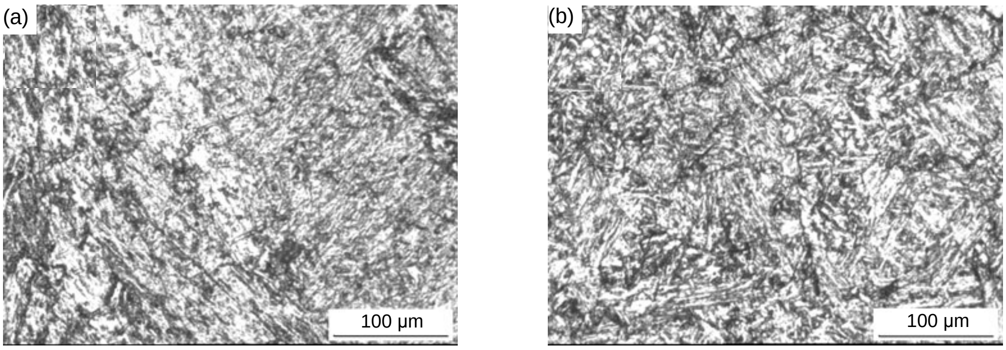


Fig. 1 Optical micrographs of weld metal. (a) Columnar grained microstructures; (b) Coarse grained microstructures

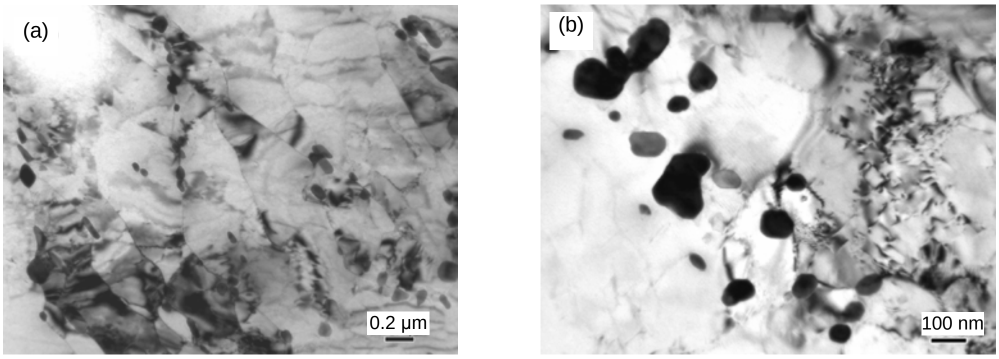
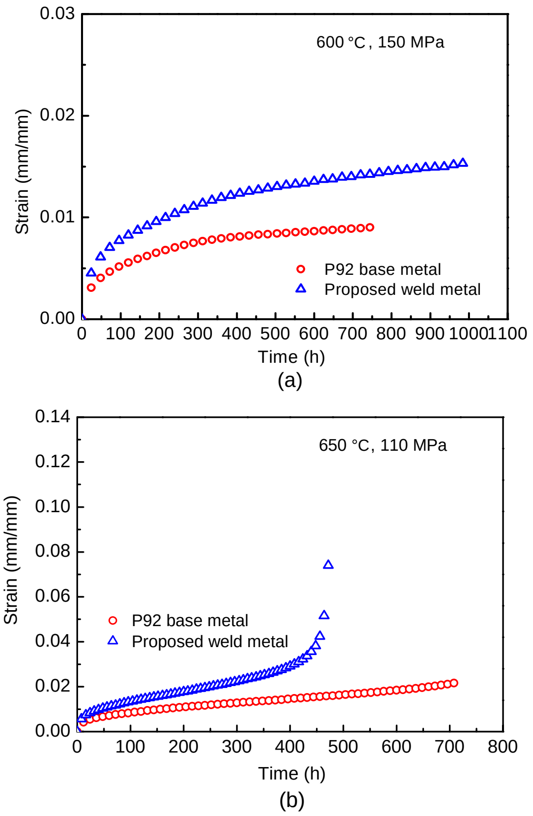


Fig. 2 Transmission electron microscopy thin foil micrographs of weld metal. (a) Lath structure; (b) Precipitates



(a)

(b)

Fig. 3 Strain-time creep curves for weld metal and the P92 base metal at (a) 600 °C, 150 MPa and (b) 650 °C, 110 MPa

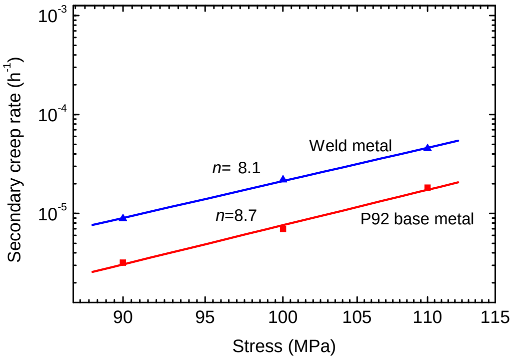


Fig. 4 Stress dependence of secondary creep rates for the weld metal and the P92 base metal at 650 °C

The secondary creep rate, depending on the applied stress, can be described by power laws, such as the well-known Norton relationship:

$$\dot{\varepsilon}_{\mathrm{m}} = A\sigma^{n}, \tag{2}$$

where $\dot{\varepsilon}_m$ is the steady creep rate, σ is the applied stress, A is a constant and n is the stress exponent. The values of A and n for the weld metal and P92 base metal are obtained from the linearised form of Eq. (2), which is presented in Table 3.

Table 3 Norton power law parameters for the weld metal and P92 base metal at 650 °C

Material	A (MPa^{-n}·h^{-1})	n
Weld metal	1.1×10^{-21}	8.1
P92 base metal	4.0×10^{-23}	8.7

The stress exponent n is considered the main parameter to identify the creep deformation mechanism, which is typically between 3 and 5 in the power law regime for pure metals and monophase materials (Knežević *et al.*, 2008). In this case, the weld metal exhibits value of the stress exponent n>8, which is close to that for P92 base metal. The high values of the stress exponent for the weld metal and P92 base metal are caused by the strengthening effect of $M_{23}C_6$ and MX precipitates in the steel (Foldyna *et al.*, 2001; Maruyama *et al.*, 2001).

4 Conclusions

The present research investigated the microstructures and creep properties of 9% Cr ferritic steel weld metal containing 1% Co, partially substituted for nickel, produced by the SAW processing. The microstructure exhibited a fully tempered martensitic structure free of δ-ferrite, with $M_{23}C_6$ carbides on sub-boundaries and fine MX precipitates within subgrains. The creep properties of the obtained weld metal are inferior to those of P92 base metal at 600 and 650 °C. The values of A and n for weld metal in the Norton power law constitution at 650 °C are 1.1×10^{-21} and 8.1, respectively.

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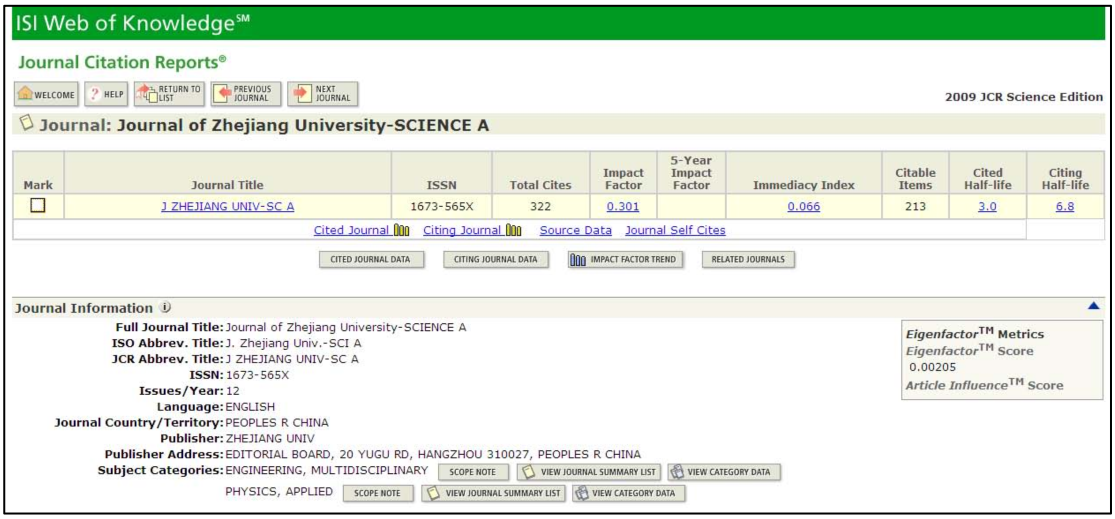

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