Development of a Filler Metal for Weldments of a Ni-Cr-W Superalloy with High Creep Strength*

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A series of weldability and creep tests of the weld metals were conducted to develop a filler metal with excellent weldability and high creep strength of the weldments of Ni-Cr-W superalloy. Contents of minor elements have a large effect on susceptibility to cracking in weldments. In particular, Zr, B, Y and Nb make the susceptibility to cracking high and addition of optimum contents of Ti or Mg reduce it slightly. A good correlation between values of the CSC (coefficient of susceptibility to cracking) of the filler metals and the weldability is recognized. On the basis of the knowledge, a filler metal with excellent weldability was developed for the Ni-18.5Cr-21W superalloy. The weld metal prepared using the developed wire possesses the creep rupture strength almost equal to that of the base metal which has a creep rupture strength above 9.8 MPa for a 1×10^5 h life at 1 000°C.

Key Words: Welding, Ni-Cr-W Superalloys, Creep Strength, Susceptibility to Cracking, Filler Metal, Minor Alloying Element, Weldability, Time to Rupture, Creep Curve, Multiple Regression Analysis

1. Introduction

Ni-Cr-W superalloys with high creep strength have been recognized as one of the most promising wrought alloys which can be used for high temperature components operated at around 1 000°C. The high-temperature gas-cooled reactor (HTGR) system utilizing nuclear heat as the heat supply for the chemical process is one of such high-temperature components. The high temperature engineering test reactor (HTTR) was constructed at Japan Atomic Energy Research Institute (JAERI)⁽¹⁾. The HTTR is a test reactor with thermal output of 30 MW and outlet coolant temperature of 850°C at the rated operation and 950°C at the high temperature test operation. From the viewpoint of efficient use of nuclear heat energy and attainment of high heat efficiency, higher temperatures of reactor outlet coolant are

advantageous. However, it is essential to develop new superalloys in order to use metallic materials at temperature of 1 000°C.

Some Ni-Cr-W superalloys possessing high creep strength were developed in the national research project concerning nuclear steelmaking in Japan⁽²⁾⁻⁽⁴⁾. After these research activities, the research and development of new heavy duty Ni-Cr-W superalloys for use at service temperatures around 1 000°C have been promoted by JAERI in cooperation with experienced authorities of industrial and academic organizations⁽⁵⁾⁻⁽¹⁰⁾. A Ni-Cr-W superalloy was developed as a result of a series of experiments^{(6),(7)}. The main chemical composition of the alloy was Ni-18.5 mass%Cr-21mass%W and the amounts of elements such as C, Mn, Si, Nb, Fe, Zr, B, Y and Ti were optimized to maintain creep strength, corrosion resistance and workability. The developed alloy has the following superior characteristics; a creep rupture strength over 9.8 MPa for a 1×10^5 h life at 1 000°C⁽⁸⁾, high corrosion resistance in HTGR helium environment⁽⁹⁾ and formability to long seamless tubes⁽¹⁰⁾.

The item to be solved in order to put the developed Ni-Cr-W superalloy to practical use is develop-

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ment of a filler metal for weldments of the superalloy. From the preliminary study, it was found that the Ni-Cr-W superalloy has high susceptibility to cracking in weldments^{(11),(12)}. Key factors to develop a filler metal for the Ni-Cr-W superalloy are improvement of weldability and attainment of high creep rupture strength of weldments. The purpose of this paper is to develop a filler metal which has superior weldability and high creep rupture strength in weldments of the Ni-Cr-W superalloy.

2. Experimental Procedure

2.1 Materials

Table 1 shows chemical composition of alloys tested in this study together with the weldability test results. The chemical composition of the main elements for the Ni-Cr-W superalloy base metal was Ni-18.5Cr-21W-0.03C-0.08Ti-0.02~0.05Zr-0.002~0.007Y-0.0035~0.006B in mass%. Ni-Cr-W superalloys have high susceptibility to cracking in weldments and amounts of minor elements contained in the alloys seem to have a large effect on weldability^{(11),(12)}. Contents of Ti, Y, Mg, Si, Mn and Al were varied in tested alloys because such elements with effects of deoxidation and desulfuration possessed possibility of improvement of weldability^{(13),(14)}. Furthermore, contents of Zr, B and Nb were varied with accumulation of results of weldability tests. All tested alloys had the following contents of elements such as P and S; P<0.01%, S<0.002%, N<0.007% and O<0.009% (in mass%). Plates with 15 mm thickness were prepared by hot-forging and hot-rolling. Filler wires with 1.2 mm diameter for automatic tungsten inert gas (TIG) welding were produced by cold-drawing and interme-

diate annealing after hot-forging and hot-rolling.

2.2 Weldability test

The following weldability tests (1)~(4) were conducted to estimate susceptibility to cracking in weldments. In addition, the following tests (5)~(8) were performed for alloys needed detail inspection.

- (1) Bead-on-plate weldability test,
- (2) FISCO cracking test,
- (3) Overlay welding test,
- (4) Bending test of welded joints,
- (5) Microstructure observation,
- (6) Hardness test,
- (7) Chemical analysis of weld metal,
- (8) Electron probe micro analyzer (EPMA) observation

Manual or automatic TIG welding was employed for weldability tests. In case of manual TIG welding, rectangular rods with a base 3 mm×3 mm were used as a filler metal. Welding current was 100~200 A and arc voltage was 11~17 V in manual TIG welding. In automatic TIG welding, welding current was 150 A at base and 170 A at peak, and arc voltage was 8~10 V. Figure 1 shows welding procedure and groove geometry of bead-on-plate welding, FISCO cracking, overlay welding and bending tests of welded joints. In the overlay welding test as shown in Fig.1(c), we performed the liquid penetration test after removing the final layer of overlay welding. The indication in the liquid penetration test of the overlay weld metal represented cracking during re-heating by multipass. Susceptibility to the cracking in overlay welding was estimated quantitatively employing the area ratio of indication in the liquid penetration test to a cross sectional area of the overlay weld metal.

Table 1 Chemical composition and weldability of tested alloys

No.	Chemical composition (mass%)													CSC*	Wa**
	C	Mn	Si	Cr	W	Ti	Zr	Y	B	Al	Mg	Nb	Ni		
S7	0.02	0.01	<0.01	18.3	21.2	0.074	0.041	0.0079	0.0023	0.028	<0.001	0.0036	Bal.	0.467	x
A	0.019	0.019	0.04	18.75	21.79	0.07	0.016	0.01	0.003	0.038	0.004	0.0041	Bal.	0.231	○
B	0.032	0.01	<0.01	18.6	21.41	0.2	0.03	0.011	0.0057	0.007	<0.001	0.033	Bal.	0.544	x
C	0.03	0.01	<0.01	18.33	21.34	0.07	0.03	0.022	0.0057	0.007	<0.001	0.032	Bal.	0.561	x
D	0.028	0.01	<0.01	18.5	21.37	0.08	0.03	0.009	0.0058	0.008	0.005	0.032	Bal.	0.536	x
E	0.03	0.01	<0.01	18.25	21.37	0.07	0.03	0.009	0.0057	0.007	0.01	0.032	Bal.	0.535	x
S5	0.04	0.01	<0.01	18.5	21.4	0.002	0.03	0.009	0.0046	0.02	<0.001	<0.01	Bal.	0.414	x
P20	0.03	0.05	0.09	18.7	21.3	0.06	0.02	0.007	0.004	0.04	<0.001	0.034	Bal.	0.424	x
P21	0.03	0.02	0.1	18.8	21.3	0.06	0.03	0.007	0.005	0.05	<0.001	0.033	Bal.	0.529	x
P22	0.03	0.06	<0.01	18.7	21.2	0.07	0.04	0.005	0.005	0.05	0.001	0.034	Bal.	0.63	x
P2	0.02	0.03	0.06	18.5	21.0	0.07	0.02	0.006	0.0016	0.06	0.001	0.02	Bal.	0.328	x
P3	0.015	0.03	0.05	18.5	21.4	0.07	0.01	0.004	0.0008	0.04	0.001	0.02	Bal.	0.216	○
P6	0.02	0.03	0.06	18.4	21.0	0.07	0.01	0.001	0.0037	0.05	0.001	0.02	Bal.	0.239	○
P41	0.024	0.03	0.06	18.4	21.6	0.07	0.02	0.004	0.0041	0.03	0.009	0.03	Bal.	0.399	x
P42	0.025	0.02	0.05	18.4	21.3	0.07	0.02	0.005	0.0042	0.03	0.007	0.03	Bal.	0.402	x
P67	0.03	0.02	0.05	18.4	21.5	0.063	<0.002	<0.001	0.002	0.052	0.001	0.02	Bal.	0.142	○
PN7	0.03	0.02	0.05	18.4	21.4	0.081	0.023	0.004	0.0024	0.066	0.002	0.02	Bal.	0.362	x
PX1	0.024	<0.02	0.08	18.28	21.68	0.08	<0.001	0.004	0.0002	0.028	0.0001	0.027	Bal.	0.155	○
PX2	0.028	<0.02	0.07	18.42	21.52	0.08	<0.001	0.005	0.002	0.026	0.0001	0.028	Bal.	0.18	○
P8	0.027	<0.02	0.06	18.5	21.5	0.06	0.006	0.003	0.003	0.02	0.002	<0.001	Bal.	0.101	○
P9	0.032	<0.02	0.058	18.5	21.5	0.07	<0.001	<0.001	0.0002	0.018	0.001	<0.001	Bal.	0.019	○

*CSC(coefficient of susceptibility to cracking in %)=10Zr+10B+5Nb+2Y

**Wa : Weldability

Fig. 1 Welding procedure and groove geometry of bead-on-plate welding, FISCO cracking, overlay welding and bending tests of welded joints (Unit : mm)

2.3 Creep test

Welded joints were manufactured using P3, PX1 and PX2 alloys chosen among alloys with good weldability shown in Table 1. Automatic TIG welding was employed and the welding condition was the same as that of the weldability tests. Creep specimens were sampled from the weld metal portion of the welded joints. The creep specimens were 6 mm in diameter and 30 mm in gauge length. Creep tests were conducted at 900, 1000 and 1050°C in air. Creep tests at 1050°C were performed for P3 weld metal specimens. Creep strain was measured and creep curves were obtained in some creep tests.

3. Results and Discussion

3.1 Weldability

Bead-on-plate and FISCO cracking tests were carried out as weldability tests at first. After that, overlay welding tests were conducted for all alloys. Bending tests of welded joints were performed for alloys which were judged to have low susceptibility to cracking in weldments from these weldability tests. Furthermore, tests such as microstructure observation and EPMA were conducted for alloys needed detail inspection.

Examples of liquid penetration tests for overlay welding are shown in Fig. 2. The cracking in weldments is observed for (a) S7, (d) S5, (e) B, (f) P20, (g) C, (h) P42 and (k) P6 alloys as shown in this figure although it is not observed for (b) A, (c) P3, (i) PX1, (j) PX2 and (l) P8 alloys. The ratio of indication area in the liquid penetration test is also indicated in this figure. Contents of minor elements such as Mn, Si, Ti, Zr, Y and B have a large effect on susceptibility to cracking in the weldments of the Ni-18.5Cr-21W alloy. From this figure, it is found that addition of Mn, Si and Y has little effect on

improvement of weldability (Fig. 2(f) and (g)). As shown in Fig. 2(d), S5 alloy with low Ti content indicates high susceptibility to cracking. In addition, decrease in Zr and B contents brings about improvement effect on weldability.

Figure 3 shows the effect of Zr and B contents on the ratio of indication area which expresses degree of the susceptibility to cracking quantitatively. It is found that Zr and B make the susceptibility to cracking high. Effect of minor alloying elements on the susceptibility to cracking can be estimated by applying multiple regression analysis to the relation between the ratio of indication area in overlay welding tests and the content of each alloying element. As a result, it was found that elements such as Zr, B, Nb and Y make the susceptibility to cracking high. These elements seem to form compounds with low melting points in welding and cause hot-cracking. The localization of Zr and Y was recognized in EPMA observation of the weld metal with high Zr and Y contents as shown in Fig. 4. Addition of Mn, Si, Y and Al results in no significant improvement on weldability. Addition of optimum contents of Ti or Mg reduces the susceptibility to cracking slightly.

Table 1 also shows results of weldability tests estimated from bead-on-plate, FISCO cracking, overlay welding tests and so on. In addition, values of coefficient of the susceptibility to cracking (CSC) in weldments are indicated. The CSC is calculated according to the following equation on the basis of the multiple regression analysis of the overlay welding test results.

$$\text{CSC}(\%) = 10\text{Zr} + 10\text{B} + 5\text{Nb} + 2\text{Y} \quad (1)$$

where contents of Zr, B, Nb and Y are expressed in mass%. The maximum value was used in the calculation for each element shown in "below" expression. A good correlation between weldability and values of the CSC is recognized. It is found that alloys with CSC values below 0.3 show good weldability. The filler metal with superior weldability can be obtained by reducing contents of Zr, B, Nb and Y with high susceptibility to cracking and by adding optimum contents of Ti or Mg.

3.2 Creep properties

Figure 5 shows the relationship between stress and time to rupture of the weld metal prepared from P3, PX1 and PX2 wires. Solid lines representing average time to rupture of the Ni-18.5Cr-21W base metal are also indicated at 900, 1000 and 1050°C in this figure. The time to rupture of the weld metal using the P3 wire is almost equal to or a little longer than that of the base metal which has a creep rupture strength over 9.8 MPa for a 1×10^5 h life at 1000°C⁽⁸⁾. The time to rupture of the weld metal using the PX2

Fig. 2 Results of liquid penetration tests after removing the final layer of overlay welding.
※ Ratio of indication area in the liquid penetration test

Fig. 3 Effect of Zr and B contents of filler metal on weld crack susceptibility. The ratio of indication area in the liquid penetration test shows susceptibility to the cracking in overlay welding.

Fig. 4 EPMA observation of Y and Zr for alloy C weld metal (Y: 0.022%, Zr: 0.03%)

Fig. 5 Relationship between stress and time to rupture of the weld metal prepared from P3, PX1 and PX2 wires. Solid lines represent average time to rupture of the Ni-18.5Cr-21W base metal.

Fig. 6 Creep curves at (a) 900°C and (b) 1000°C for the weld metal prepared from P3, PX1 and PX2 wires. Creep curves of the Ni-18.5Cr-21W base metal are also indicated.

wire is almost equal to that of the base metal although it becomes a little shorter than that of the base metal under a condition of a lower stress level at 1000°C. On the other hand, the time to rupture of the weld metal using PX1 wire is clearly shorter than that of the base

metal and the weld metal using the P3 and PX2 wires.

Figure 6 shows creep curves of each weld metal in comparison with those of the base metal at 900°C under 39.2 MPa and 1000°C under 19.6 MPa. The steady-state creep rates of all weld metals prepared using P3, PX1 and PX2 wires are lower than those of the base metal. However, rupture strain is small in the weld metals. Furthermore, time from onset of a tertiary creep stage to rupture is short in most cases of the weld metals. At 1000°C, a tertiary creep stage starts earlier in the weld metal than in the base metal. In the case that time to rupture of the weld metal is shorter than that of the base metal, the causes are early onset of a tertiary creep stage and reduction of rupture strain.

It is useful to examine the relationship between time to rupture of the weld metal and contents of minor alloying elements. As shown in Fig. 5 the time to rupture of PX1 weld metal is shorter than that of the base metal although the time to rupture of P3 weld metal is almost equal to that of the base metal. Contents of elements such as Mn, Si, Ti, Zr, Y and B are adjusted in P3, PX1 and PX2 alloys so that they have good weldability. Zirconium content is 0.01% in P3 alloy, and <0.001% in PX1 and PX2 alloys, respectively. Boron content is 0.0008% in P3 alloy, 0.0002% in PX1 alloy and 0.002% in PX2 alloy, respectively. It has been recognized that Zr and B make creep rupture strength and rupture ductility high^{(15)–(17)}. Contents of Zr and B were reduced in PX1 alloy as low as possible to obtain superior weldability. It is considered that this is the cause of low creep rupture strength of PX1 weld metal. However, high contents of Zr and B result in high susceptibility to the cracking. Therefore, it is necessary to add a small amount of these elements within a certain range where weldability is not damaged in order to obtain good creep properties of the weld metal.

4. Conclusions

A series of weldability and creep tests of the weld metals were conducted for the purpose of development of a filler metal with excellent weldability and high creep rupture strength of the weldments of Ni-Cr-W superalloy. The results obtained were as follows:

1. Contents of minor elements have a large effect on susceptibility to cracking in weldments of the Ni-18.5Cr-21W superalloy. According to the results of weldability tests, Zr, B, Y and Nb make the susceptibility to cracking high and addition of optimum contents of Ti or Mg reduce it slightly. A good correlation between values of the CSC ($=10Zr+10B+5Nb+2Y$) of the filler metals and the wel-

dability is recognized. Good weldability is obtained for filler metals with CSC values below 0.3.

2. The weld metal prepared using the developed filler wire possesses the creep rupture strength almost equal to that of the base metal which has a creep rupture strength above 9.8 MPa for a 1×10^5 h life at 1000°C. It is important to balance and optimize the content of minor elements affecting weldability and creep properties in order to obtain a filler metal with excellent weldability and high creep rupture strength of weldments.

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