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MECHANISTIC STUDY OF HOT CRACKING AND DEVELOPMENT OF NEW RESISTANT NI-BASED HIGH-CR ALLOY WELD METAL

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Abstract

Alloys 52/152 are commonly used as weld metals of 30% Cr-Ni based alloy in the world PWRs. However, these alloys show high susceptibility to ductility-dip cracking (DDC) as one kind of hot cracking. In order to improve the DDC susceptibility of Alloys 52/152, the effect of the chemical composition on DDC susceptibility of 30% Cr-Ni based alloys was studied on 18 laboratory melted heats by many kinds of hot cracking testing, comparing with a commercial heat of Alloy 52.

Hot cracking susceptibility based on the Longi-Varestraint test and On-cooling hot ductility test seems to be appropriate for the evaluation of solidification and liquation cracking susceptibility, but not so suitable for the evaluation of DDC. In case of strain-to-fracture (STF) test, DDC occurred in the temperature range of 900 to 1,000°C. However, this temperature range is different from the ductility-dip cracking temperature range obtained by high temperature tensile testing.

The authors studied a novel thermal cycling test under tensile loading of the round-notched bar type specimen, using Gleeble test machine. In this kind of testing the mechanism of the DDC is thought to be different from the earlier observations and hypotheses. The DDC initiation and fracture temperatures were measured in the temperature range of 1000 to 1150°C for the 30% Cr-Ni based alloys. The DDC susceptibility was markedly improved by the addition of C and Nb contents.

1. INTRODUCTION

In the field of Ni-based high-Cr alloys such as Alloy 52 or 152, the mitigation of the hot cracking, especially the ductility-dip cracking (DDC), is the main research topic [1].

In order to develop the new highly resistant filler metals to hot cracking, the authors have started to study the effects of chemical composition on hot cracking susceptibility of Ni-based alloys using 10 laboratory heats by Longi-Varestraint and some other tests comparing with commercial Alloy 52.

However, the characteristics of hot cracking were shown to be different based on the individual test technique. Especially, DDC susceptibility was quite different in each test technique. The mechanism of DDC is hypothesized to occur by the strain ratcheting mechanism, recently [2].

In order to develop the proper test method for evaluating the hot cracking susceptibility, especially DDC susceptibility, and new highly resistant filler metals to hot cracking, the authors have studied the effects of chemical composition on hot cracking susceptibility of 30% Cr-Ni based alloys using laboratory melted heats and commercial Alloy 52 filler wire by conventional hot cracking tests and new Gleeble tests.

2. EXPERIMENTAL PROCEDURES

In this study, 10 heats were fabricated by 1 kg button melting in vacuum. These buttons were soaking heat treated at 1200^{o}C and hot rolled to the sheets of 6 mm thick and 70 mm wide. The sheets were solution heat treated at 1100^{o}C and applied to Longi-Varestraint testing. According to the Longi-Varestraint test results, 5 heats were melted by 50 kg laboratory vacuum induction melting (VIM) process and the ingots were soaking heat treated at 1200^{o}C and hot rolled to the sheets of 6 mm thick and 70 mm wide. Some of the 50 kg VIM heats were hot forged to the bars of 70 mm diameter. The bars were fabricated to the 1.6 mm diameter filler wire by hot rolling and cold pilgering process. Hot-rolled sheets were solution heat treated at 1100^{o}C and applied to Longi-Varestraint testing. After that, additional 3 heats were produced by the same button melting process and fabricated to the sheets of 6 mm thick and 70 mm wide and 1.6 mm diameter filler wire. Together with a commercial Alloy 52 1.6 mm diameter filler wire they were applied to the various hot cracking tests.

The chemical compositions of the 13 heats of buttons, 5 heats of the 50 kg VIM ingots one commercial filler wire heat are shown in Table 1. Using the 1.6 mm diameter filler wires of the laboratory melted heats and commercial Alloy 52, the five-passes four-layered beads build-up (FPFLB) test specimens (FPFLB test specimen: similar to fissure-bent test specimen [3]) were manufactured. The FPFLB test specimens were fabricated by the five passes for one layer and four-layered beads build-up on the laboratory melted Alloy 690 sheets and finally wash beads were done on the top of the four-layered beads build-up.

On the other hand, using the above wires, large two-pass beads were build-up on the laboratory melted Alloy 690 sheets, and On-cooling hot ductility test specimens [4], thermal cycling test specimens and high temperature tensile test specimens were machined from the large two-pass beads. Also, using the above wires, STF test specimens were manufactured according to Nissley and Lippold [1].

The Longi-Varestraint tests were conducted under the conditions of 125 A of welding current, 10 V of welding voltage and 8 cm/min of welding speed. FPFLB test specimens were welded under conditions of 100 A of welding current, 10.5 V of welding voltage, 12 cm/min of welding speed and 28 cm/min of wire feed rate. The large two-pass beads build- up for the On-cooling hot ductility test specimens were welded under the conditions of 200 A of welding current, 12.5 V of welding voltage, 10 cm/min of welding speed and 170 cm/min of wire feed rate. Finally, in accordance to the above Longi-Varestraint test, On-cooling hot ductility test and the FPFLB test, high temperature tensile test, thermal cycling test and STF test were conducted using Gleeble test machine.

3. RESULTS AND DISCUSSIONS

The Longi-Varestraint test results for 13 heats of 1 kg laboratory button melts and 5 heats of 50 kg laboratory VIM ingots are shown in Fig.1. In the Longi-Varestraint testing, heats No. 9, 09R/TD9 and WT showed excellent hot cracking resistance, comparing with the laboratory heats of simulated Alloy 52 (heat No. 3) and 132 (heat No. 10). Heats No. 9, and 09R/TD9 have the extra low C, P, S, Si, Nb, Ti, Al contents and heat WT has the extra low P, S, Si, Nb, Al contents and medium C and Ti contents, comparing with Alloy 52 heat.

In the "On-cooling hot ductility test" same as Noecker and DuPont [5] test, the all-weld metal specimens which were made with commercial Alloy 52 wire showed ductility loss at 900 to 1000°C. But, the all-weld metal specimens which were made of laboratory heat No. 09R/TD-9 wire (same chemical composition as No. 09R/TD9) showed no remarkable ductility loss at 800 to 1000°C.

There seems to be no significant difference for the evaluation of hot cracking susceptibility between the Longi-Varestraint test and On-cooling hot ductility test. On the other hand, the FPFLB test specimens were made using the commercial Alloy 52 and laboratory heat 09R/TD9 and WT wires. These specimens were cross-sectioned and observed by optical microscopy after polishing and etching. In the specimens made of commercial Alloy 52 wire, no hot cracks were detected in any locations, but many hot cracks were detected in the specimens made of laboratory heat WT wire and some cracks were detected in the specimens made of 09R/TD9 wire. The evaluation of hot cracking susceptibility by Longi-Varestraint test and On-cooling hot ductility test was quite different from that observed by FPFLB test.

Recently, the mechanism of DDC is hypothesized to occur by the strain ratcheting mechanism [2]. It is well known that the strain ratcheting mechanism happens under three-dimensional stress. So, the authors expected that the DDC can be reproduced by the novel thermal cycling test for the round-notched specimen under tensile pre-load. The novel thermal cycling tests were conducted for the round-notched bar specimens under tensile pre-load. Thermal cycling tests were done as one cycle for 200 to 1200°C, 200 to 1100°C, 200 to 1000°C, 200 to 900°C, 200 to 800°C, 200 to 700°C, 200 to 800°C, 200 to 900 °C, 200 to 1000°C, 200 to 1100°C and 200 to 1200°C. The novel thermal cycling test was done by induction heating in pure Ar gas atmosphere at about 50°C/s heating rate without hold time at highest temperature and cooling in pure Ar gas at about 50°C/s cooling rate. At the time of the novel thermal cycling test, specimen temperature, tensile load, and displacement of the loading head were recorded. Commercial heat Alloy 52 and laboratory heat of 09R/TD9 showed a low toughness in the novel thermal cycling test, but the simulated 52 MSS [5] laboratory heat showed good toughness, and the controlled Nb and C content laboratory melt heat B1 showed excellent toughness, as shown in Fig.4 and Fig.5. These tendencies are same as the FPFLB test results. In each thermal cycling test specimen, crack initiation and fracture temperatures were measured in the temperature range between 1,000 to 1,150°C. The high temperature tensile tests using all-weld metal specimens were conducted at the temperature range between 850 to 1200 °C to confirm the DDC temperature range. From the high temperature tensile tests, the elongation to fracture was decreased in the temperature range of 1,000 to 1,150°C and the reduction of area was decreased at 1,050°C, but not at 850 to 1,000°C, as shown in Fig.6.

On the other hand, the STF testing for the specimens made of commercial heat Alloy 52 wire and 09R/TD-9 wire was conducted according to the welding process and test procedures of Nissley and Lippold [1]. In the STF tests, DDC was reproduced in the specimens of 09R/TD-9 in the temperature range between 900 to 950^{o}C, but not observed in the specimens of commercial Alloy 52 wire, as shown in Fig.7.

From these results, the mechanism of the DDC is thought to be different from the earlier observations and hypotheses of DDC[1], and a new 30% Cr-Ni based alloy for improving the hot cracking resistance is proposed.

4. CONCLUSIONS

The effect of chemical composition on hot cracking susceptibility of 30% Cr-Ni based alloys was studied on 18 laboratory melted heats and commercial heat of Alloy 52 by conventional hot cracking and Gleeble tests. Hot cracking susceptibility of the test materials was evaluated by Longi-Varestraint test, On-cooling hot ductility test, FPFLB test, thermal cycling test, STF test using Gleeble test machine. High temperature tensile testing was done to confirm the DDC temperature range.

Hot cracking susceptibility based on the Longi-Varestraint test and On-cooling hot ductility test was improved by decreasing of eutectic formation elements such as C, P, S, Si, Nb, Ti, Al. The hot cracking susceptibility based on the FPFLB test and thermal cycling test was not improved by decreasing of eutectic elements, but improved by the addition of C and Nb contents. From these studies, it is concluded that the Longi-Varestraint and On-cooling hot ductility tests are able to evaluate the solidification cracking and liquation cracking, but they are not proper tests to evaluate the DDC susceptibility. The FPFLB test and thermal cycling test are able to evaluate the DDC susceptibility. The DDC may occur by the strain ratcheting mechanism. Based on the test results a novel Gleeble test is recommended to evaluate the DDC susceptibility, and a new 30% Cr-Ni based alloy for improving the hot cracking resistance is proposed.

5. ACKNOWLEDGEMENT

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Table 1 Chemical compositions of laboratory melts and commercial Alloy 52.

		Feature	C	Si	Mn	S	Ni	Cr	Fe	Mo	Al	Nb	Ti
1Kg Button Lab. Melt	No.1	High Si, M, LowNb	0.019	0.72	2.18	0.0008	56.30	29.96	9.04	–	0.816	0.08	0.81
	No.2	Low Si, Mn,LowNb	0.028	0.10	0.10	0.0017	58.94	30.04	9.04	–	0.815	0.09	0.80
	No.3	Simulate Alloy 52,LowNb	0.024	0.35	0.99	0.0010	57.88	29.94	9.02	–	0.816	0.08	0.80
	No.4	7%Fe,LowNb	0.023	0.36	2.17	0.0010	58.50	30.10	7.06	–	0.794	0.08	0.80
	No.5	5%Fe,LowNb	0.022	0.37	2.18	0.0010	60.72	29.90	5.02	–	0.787	0.08	0.81
	No.6	3%Fe,LowNb	0.023	0.35	2.18	0.0009	62.53	30.08	3.04	–	0.786	0.08	0.80
	No.7	1.5%Fe,LowNb	0.023	0.36	2.19	0.0008	63.99	30.09	1.56	–	0.787	0.08	0.80
	No.8	0.5%Fe,LowNb	0.022	0.37	2.17	0.0009	65.70	29.96	0.43	–	0.795	0.08	0.80
	No.9	Pure 3%Fe,LowNb	0.006	0.10	0.99	0.0005	65.80	29.94	3.05	–	<0.002	<0.002	0.002
	N0.10	Simulate LowC, Alloy 132	0.007	0.22	2.8	0.0008	70.50	14.98	9.48	–	<0.003	1.81	<0.002
50Kg VIM Lab. Melt	09R/TD9	Low C,Si,Al,Nb,Ti	0.005	0.12	0.53	0.0006	66.22	30.38	2.60	–	0.064	≦0.002	0.003
	ZT	LowC,Si,Nb,Ti	0.003	0.10	0.50	0.0010	60.09	29.89	9.54	–	0.036	≦0.002	≦0.001
	WT	Med.C,Al,LowNb,Ti	0.020	0.13	0.51	0.0010	60.10	29.86	8.92	–	0.086	0.069	0.35
	VT	Med.C,Al,Nb,Ti	0.016	0.10	0.52	0.0010	59.96	30.1	8.92	–	0.046	0.10	0.25
	XT	Med.C,highNb,LowAl,Ti	0.021	0.12	0.53	≦0.0010	60.47	28.02	8.10	–	≦0.005	2.62	≦0.01
1Kg Button Lab. Melt	B1	High C,Nb,Med.Ti,LowAl	0.030	0.01	0.96	0.0010	55.85	30.19	6.90	≦0.01	0.19	2.47	0.30
	B2	Med.C, Low Si, Al, Med.Nb,Ti	0.023	0.01	0.98	≦0.001	58.70	30.08	7.55	≦0.01	0.19	1.97	0.30
	52MSS	Simulate Alloy 52MSS	0.020	0.01	0.97	0.0010	58.71	30.15	3.00	4.02	0.19	2.47	0.30
Commercial	市販52	INCO Alloy 52	0.027	0.16	0.24	≦0.001	60.52	28.8	8.99	0.01	0.71	0.01	0.50
			🟥	: Reduced element				🟨	: Increased element				

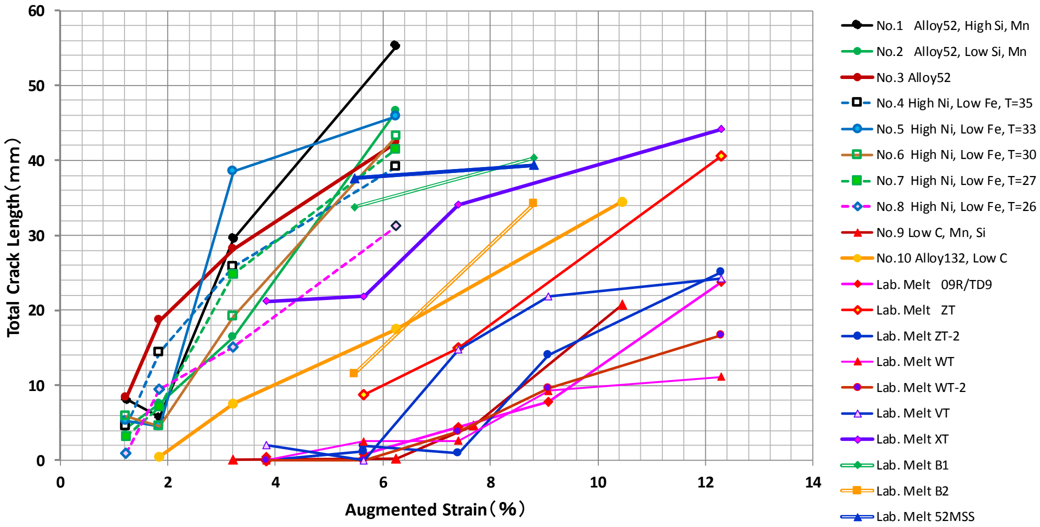

Fig.1 Varestraint test results for all laboratory melt heats.

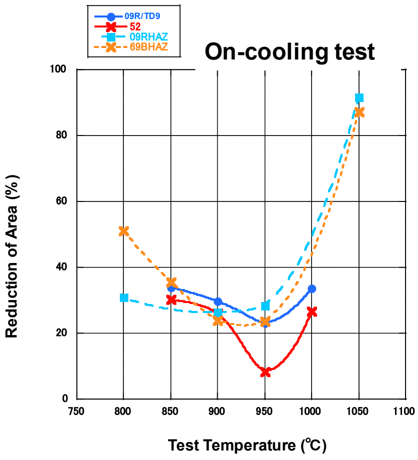

Fig.2 Hot-ductility test results from On-cooling testing.

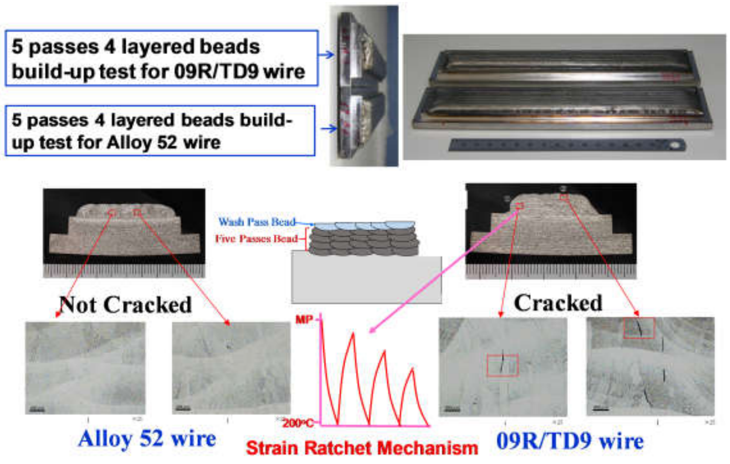

Fig.3 Microscopy of the cross-sections for four-pass layered build-up and wash bead test specimens using commercial Alloy 52 and 09R/TD9 wires.

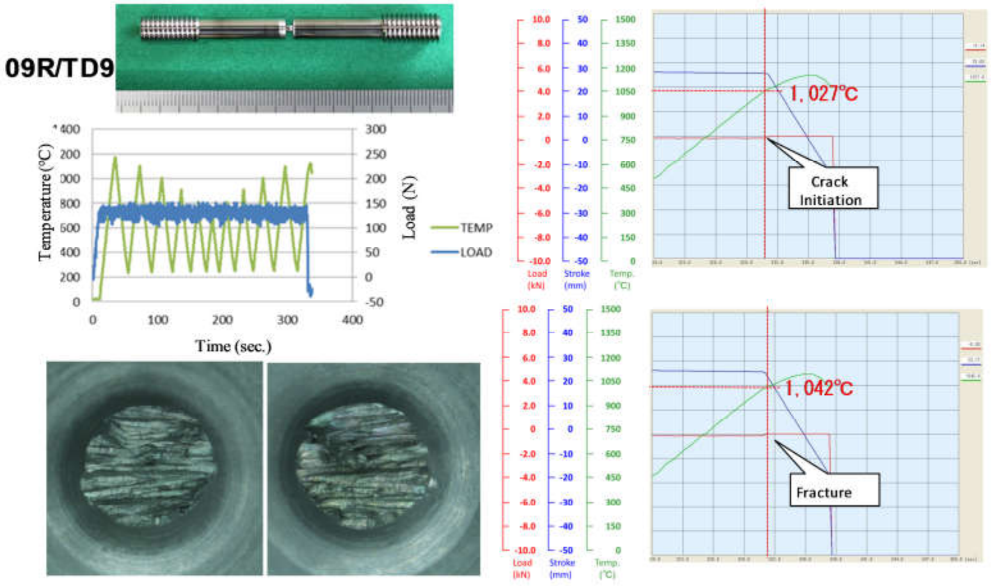

Fig.4 Thermal cycling test results for lab. melt 09R/TD 9. (Preload: 46 MPa)

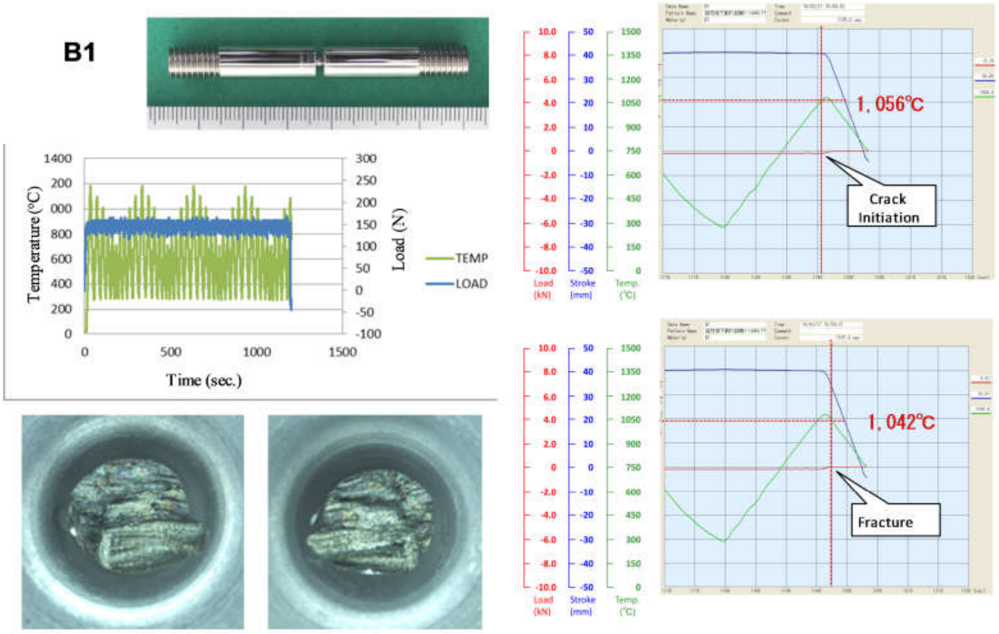

Fig.5 Thermal cycling test results for lab. melt B1. (Preload: 46 MPa)

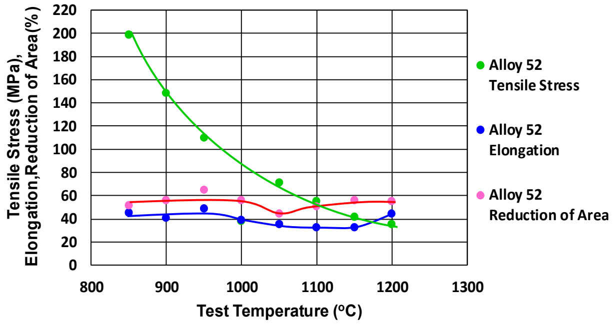

Fig.6 High temperature tensile test results for Alloy 52.

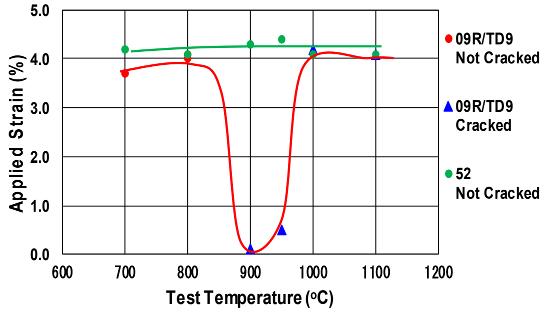

Fig.7 Strain-to-fracture test results for Alloy 52 and laboratory heat of 09R/TD9.