Effect of Sulfur Contents and Welding Thermal Cycles on Reheat Cracking Susceptibility in Multi-pass Weld Metal of Fe-36%Ni Alloy

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ABSTRACT This study has been conducted to clarify the effect of sulfur content and welding thermal cycles on reheat cracking susceptibility in the multi-pass weld metal of Fe-36%Ni alloy. Reheat cracking occurred in the preceding weld pass reheated by subsequent passes. Microscopic observations showed that reheat cracking propagated along grain boundaries which resulted in intergranular brittle fractures. The region where reheat cracking occurred and the number of cracks increased with the increase in sulfur content of the alloys. These experimental results suggested that reheat cracking was associated with the embrittlement of grain boundaries, which was promoted by sulfur and subsequent welding thermal cycles. AES analysis indicated that the sulfur segregation occurred at grain boundaries in the reheated weld metal. On the basis of these results, the cause of reheat cracking in multi-pass welding can be attributed to hot ductility loss of weld metals due to sulfur segregation which was accelerated by the reheating with multi-pass welding thermal cycles.

1. Introduction

Invar (Fe-36%Ni) alloy has a low thermal expansion coefficient and exhibits good low-temperature toughness due to its full austenitic structure. Therefore, this alloy is a suitable material for cryogenic applications such as the tanks of LNG carriers [1], liquid fuel transport pipes [2,3] and underground LNG membrane tanks [1]. Invar alloy is, however, more susceptible to weld cracking than an austenitic stainless steel that is commonly used for these storage containers. In particular, cracking which occurs in the regions of weld metals reheated on multi-pass and/or repair welding is a confronting problem in construction of heavy sectioned Invar alloy [4,5]. It has been reported that all of the reheat cracks occurred at grain boundaries in Invar alloy weld metal reheated by subsequent passes, and the increase in impurities, typically sulfur, in Invar alloys caused increased reheat cracking susceptibility [1]. On the basis of these reports, reheat cracks occurring in the weld metals of Invar alloys seems to be generally recognized as ductility-dip cracks. However, the effect of impurities in detail and/or the mechanism of reheat cracking in weld metals of Invar alloys are still uncertain.

Therefore, in order to clarify the mechanism of reheat cracking in multi-pass weld metal of Invar alloys in this study. Special attention has been paid to the effect of sulfur segregation on grain boundaries, which may be accelerated by reheating in multi-pass welding.

2. Experimental Procedures

The materials used in this investigation were Fe-36%Ni type Invar alloys varied in sulfur content to investigate the effect of sulfur on reheat cracking susceptibility in weld metals. Chemical compositions of the alloys are indicated in Table 1. The double-bead and triple-bead longitudinal Varestraint tests were used for evaluation of reheat cracking susceptibility in these alloys. The preceding weld bead was reheated by the subsequent weld pass and was subjected to the strain of bending in the double-bead longitudinal Varestraint test. On the other hand, the preceding weld pass was reheated twice by subsequent weld passes in the triple-bead test. The voltage and current of welding for these tests were 14V and 120A, respectively. The melt runs were made at 1.67mm/s. The augmented strain in Varestraint tests was varied to 1.6%, 2.4% and 3.5%.

Table 1 Chemical compositions of materials used (mass%).

Mark	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Al	N	O
IN0	.18	.10	.09	<.001	<.001	<.01	35.94	<.01	<.01	<.01	.001	.0004	.001
IN3	.20	.10	.10	<.001	.004	<.01	35.17	<.01	<.01	<.01	.002	.0003	.001
IN4	.21	.11	.10	<.001	.011	<.01	36.12	<.01	<.01	<.01	.002	.0003	.001

3. Results and discussion

To elucidate the effect of sulfur on hot cracking susceptibility in the weld metal of Invar alloys reheated, the double-bead and triple-bead longitudinal Varestraint tests were performed. Figure 1 shows the surface of the weld metal of alloy IN4 after the double-bead longitudinal Varestraint test, when an augmented strain of 1.6% was applied. Many cracks were observed in the surface of preceding weld pass reheated by a subsequent pass. Cracks preferentially occurred along the growth direction of columnar grains and/or around the center line of the preceding weld bead. Microscopic observation of the fractured surface revealed that the specimens were fractured in a brittle manner characterized by columnar grain boundary fracture, as shown in Fig.2. The edge of the columnar grains was observed clearly and the appearance of liquation was unrecognized. On the basis of these microscopic observations, reheat cracks which occurred in the preceding weld pass were considered to be ductility-dip cracks.

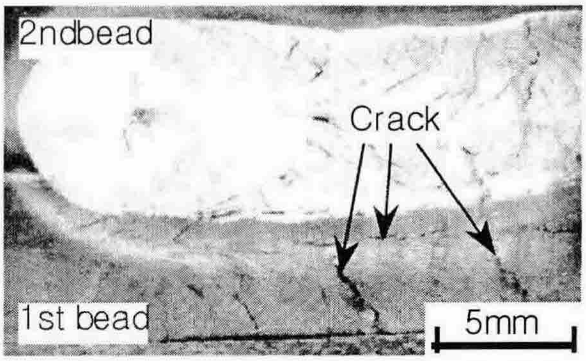


Figure 1 Appearance of specimen after double-bead Varestraint test (IN4, augmented strain: 1.6%).

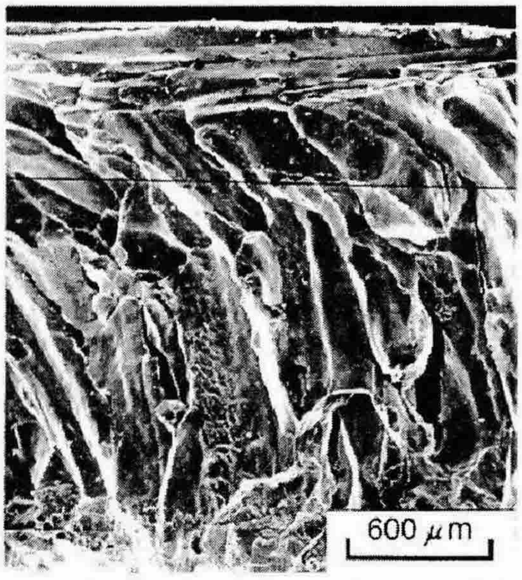
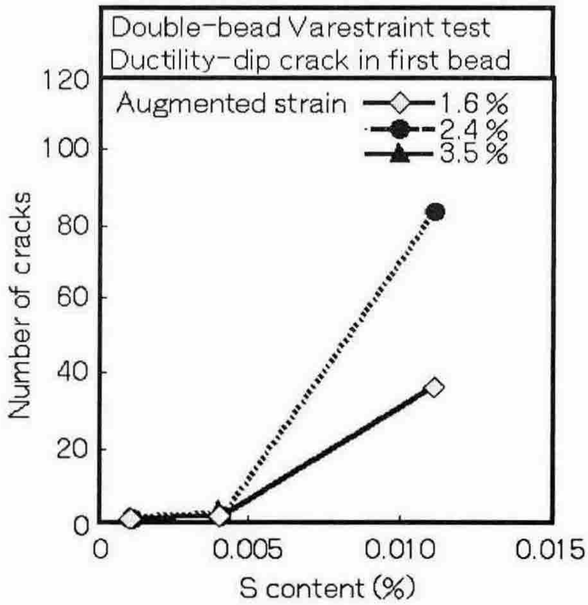
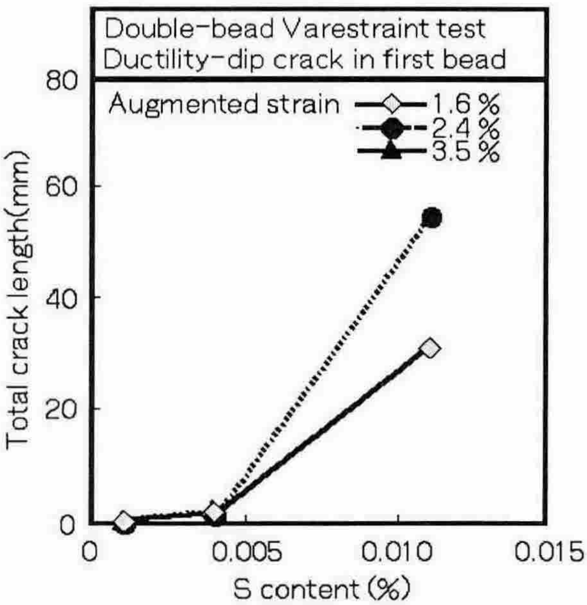


Figure 2 Fractgraph of the crack occurred in the specimen after double-bead Varestraint test (IN4, augmented strain: 1.6%).

Figure 3 shows that the relationship between the sulfur content in the specimens and the number and the total length of reheat cracks which occurred in the preceding weld pass. The number and the total length of reheat cracks were increased with an increase in the sulfur content in the specimen. Especially, when the sulfur content in the specimen was increased more than 0.004%, the number and total length of reheat cracks were rapidly increased. These experimental results apparently indicate that reheat cracking susceptibility in the weld metal is extremely sensitive to the sulfur content and is markedly promoted by the increase in sulfur content in the materials.



(a) Number of cracks



(b) Total crack length

Figure 3 Relationship between S content and number of cracks and total crack length.

On the other hand, to elucidate the effect of reheating, the reheat cracking susceptibility of the preceding weld pass reheated twice by subsequent passes was examined by the triple-bead longitudinal Varestraint test. Figure 4 indicates the comparison of reheat crack sensitivity in the first bead examined by the double and triple-bead Varestraint tests. The total length of reheat cracks in the triple-bead test were much larger than that in the double-bead test. In addition, such tendency was markedly recognized in the peak temperature range between 1000K and 1100K. These experimental results suggested that reheat cracking was promoted not only by the sulfur content in the material but also by reheating with subsequent welding thermal cycles.

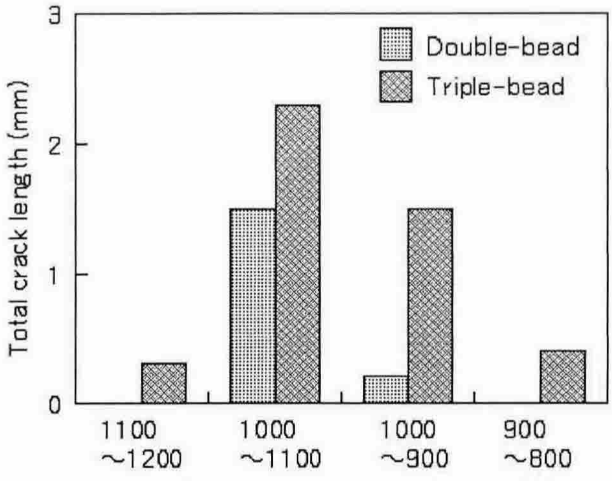
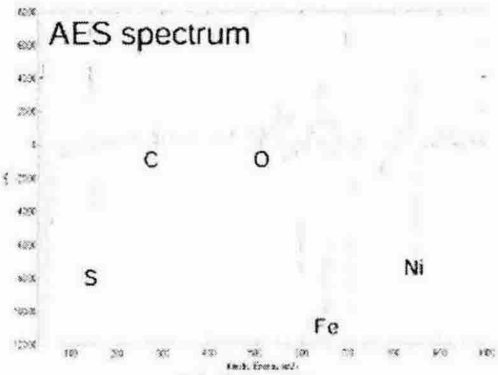


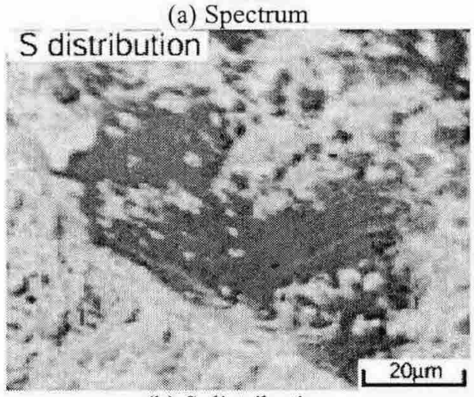
Figure 4 Effect of peak temperature reheated by subsequent pass on total crack length in first bead.

As described above, the reheat cracking in the weld metals of Invar alloys was found to occur at grain boundaries. It is known that segregation of surface active elements tends to occur on grain boundaries, which leads to embrittlement of the grain boundaries. Therefore, in order to elucidate the effect of thermal cycles on sulfur concentrations at the grain boundaries, AES analysis was conducted for the fractured surface of weld metals reheated twice and three times at peak temperature of 1000K. The spectrum and sulfur distribution at fractured surfaces were demonstrated in Fig.5. These results indicated that sulfur was widely distributed at grain boundaries. In addition, the sulfur content at fractured surfaces was evaluated by AES analysis. As weld metals reheated twice, the sulfur content was about 7%. On the contrary, in the case of reheating three times, the sulfur content was about 9%.

On the basis of these results, it is apparent that the cause of reheat cracking in the multi-pass welding can be attributed to grain boundary embrittlement due to sulfur segregation which was accelerated by the increase in welding thermal cycles.



(a) Spectrum



(b) S distribution

Figure 5 Results of AES analysis (IN4, weld metal).

4. Conclusions

The effects of sulfur and welding thermal cycles on reheat cracking susceptibility of Fe-36%Ni Invar alloys in multi-pass welding were investigated in this study. According to the Varestraint test results, the number and total length of reheat cracks occurred in the preceding weld pass reheated by subsequent passes were increased with the increase in sulfur content in the alloys. In addition, the reheat cracking susceptibility in the weld metal subjected to reheating twice by subsequent passes was much higher than that subjected to reheating only once by a subsequent pass. AES analysis revealed that the enhanced susceptibility to reheat cracking of multi-pass welding in Invar alloys can be attributed to the grain boundary embrittlement, due to sulfur segregation at the grain boundaries, which is accelerated by reheating by the subsequent weld passes.

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