Solidification Crack Susceptibility in Weld Metals of Fully Austenitic Stainless Steels (Report IX)†

–Effect of Titanium on Solidification Crack Resistance–

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Abstract

The effect of titanium(Ti) addition on the solidification crack susceptibility of commercially available SUS 310S (AISI 310S) was investigated by the Trans-Varestraint test and three practical hot cracking tests. These results indicated that an optimum content of Ti addition was greatly beneficial to the improvement of the cracking resistance of SUS 310S weld metals containing about 0.024%P and 0.002%S, but on the contrary an excess of Ti content was harmful. The beneficial effect of Ti addition was interpreted in terms of the formation of higher melting point microconstituents including Ti.

KEY WORDS: (Austenitic Stainless Steels) (Weld Metals) (Hot Cracking) (Weldability Tests) (Titanium)

1. Introduction

Fully austenitic stainless steels are recognized to be susceptible to weld solidification cracking. Therefore, a large number of studies have been conducted to elucidate the cause of cracking and to improve cracking susceptibility.[1)-4)] A series of intensive work at the JWRI[4)-15)] has defined the degree of the solidification crack susceptibility of commercial austenitic stainless steels, the mechanism of solidification cracking, the behavior of δ-ferrite at high temperatures, the beneficial effect and role of δ-ferrite in reducing cracking in SUS 304 weld metal, the degrees of the detrimental effect of P and S and the favorable effect of REM and Mn addition on the cracking resistance of SUS 310S type 25%Cr-20%Ni stainless steels.

This investigation was also undertaken to develop crack-resistant fully austenitic stainless steels. Since the previous paper[10)] revealed that an optimum content of Ti reduced the cracking susceptibility of SUS 310S steels containing about 0.03%P and 0.05%S, the effect of Ti addition on the cracking resistance of commercially available SUS 310S steels was further examined by performing the Trans-Varestraint test and three hot cracking tests to confirm that Ti was beneficial in preventing cracking.

2. Review of Solidification Cracking Studies

Figure 1 shows schematic illustration of solidification mode near solid-liquid interface and liquid behavior at solidification grain and cellular dendritic boundaries, as shown in the previous papers[4),6),13)] based on the observation of the microstructure of SUS 310S fully austenitic stainless steel weld metals quenched during GTA welding and the fractography of solidification cracks induced by the Trans-Varestraint test. P and S are easy to segregate to solidification boundaries and consequently lower the nominal solidus temperature, and liquid droplets enriched in P and/or S are formed in the boundaries below the solidus temperature. In most cases, solidification cracking occurs at solidification grain boundaries filled with liquid at high temperatures between the liquidus and the solidus temperature, and propagates along migrated grain boundaries joining liquid droplets.[4),12),13)]

Phosphides and sulphides were investigated to know the degree of the segregation of P and S and the amount and behavior of liquid droplets.[4),6),9)] **Table 1** gives a summary of characteristics of phosphides and sulphides. Sulphides are easier to form than phosphides but the melting point of phosphides are about 200°C lower than that of sulphides. In the case of commercial levels of about 0.02%P and 0.003 to 0.007%S, P is regarded as a

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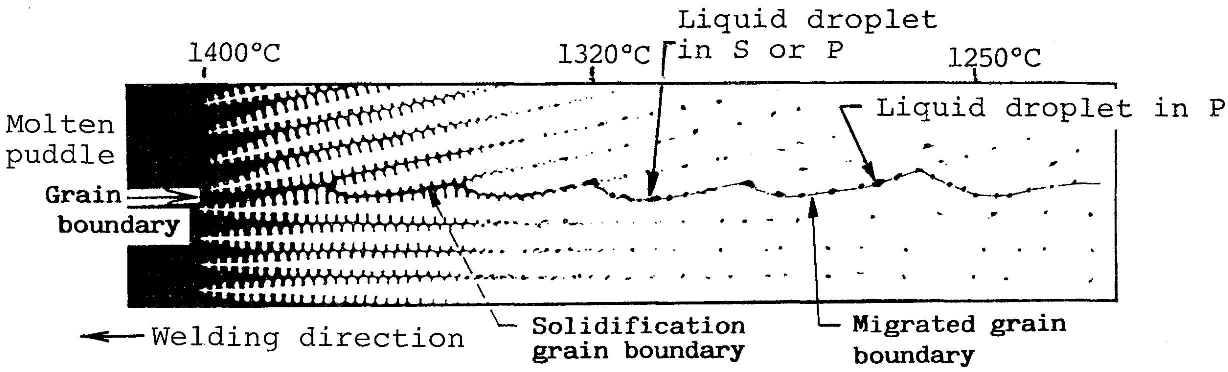


Fig. 1 Schematic representation of solid-liquid interface during solidification of SUS 310S weld metal containing commercial levels of P and S.

Table 1 Summary of physical properties of phosphide and sulphide in SUS 310S weld metal.

Element	Type of inclusion	Structure type	Main element	Content (%) of P or S	Number of inclusion (1/0.01mm²)	Area percentage (%)	Main morphology	Melting point (°C)
Phosphorus	Phosphide	M_3P bct a=9.14Å c=4.57Å	Cr, Fe P	0.003 0.007 0.021 0.055 0.240	0 2 42 - -	0 0 0 0.1 0.45	- Granular G.+Rod-like G.+R.+Film-like G.+R.+Film-like	about 1060 - 1100
Sulphur	Sulphide	α-MnS fcc a=5.22Å	Mn, Cr S	0.003 0.007 0.012 0.017 0.199	2 11 48 167 -	0 0 0 0.08 0.53	Globular Globular G.+Rod-like G.+Rod-like G.+Rod-like	about 1280 - 1310

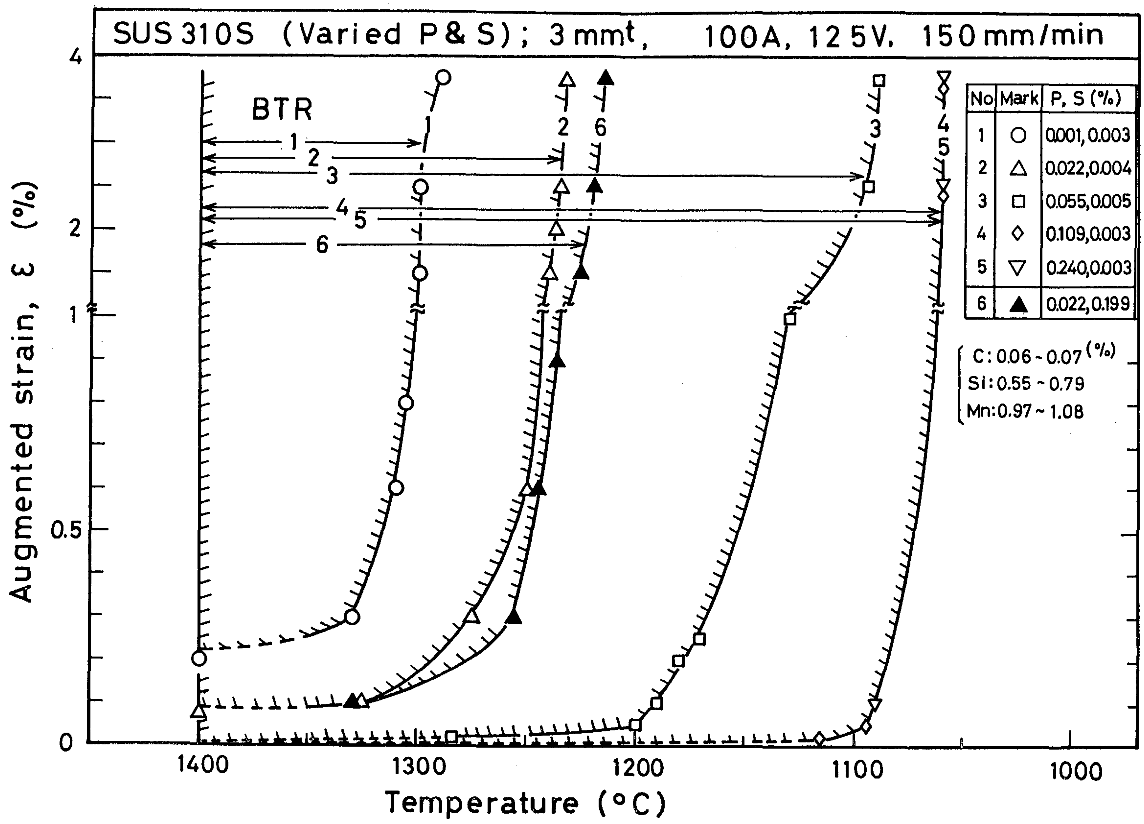


Fig. 2 Effect of P and S on ductility curves of BTR for SUS 310S weld metals.

more detrimental element to cracking than S because the number of phosphides is larger and the solidification temperature of phosphides is lower.

Figure 2 indicates the effect of P and S on ductility curves and the BTR for SUS 310S type 25%Cr-20%Ni alloys.[7),9)] Since the BTR widens gradually with increases in P content and the related liquid amount, it is apparent that P is extremely deleterious to cracking. The harmful effect of P is ascribed to a high degree of segregation and the formation of low solidification temperature liquids. In the case of commerical SUS 310S containing 0.022%P and 0.004%S the lower temperature limit of the BTR at $\epsilon = 2.5\%$ is about 1240°C, which is lower than the solidification temperature of sulphides but higher than the solidification temperature of phosphides.

Therefore, metallurgical procedures to decrease the segregated degree of P by the fixation or dephosphorization or to raise the solidification temperature of phosphides by the addition of a certain beneficial alloying element are taken into consideration to reduce the BTR and cracking susceptibility. From this viewpoint the authors[10)] found out the beneficial effect of La and REM (mish metal including La, Ce, etc.) additions and the feasibility of the beneficial effect of Ti addition on improvement of the cracking resistance of commercial SUS 310S.

3. Materials and Experimental Procedures

Ti additions were made to commercially available SUS 310S with the compositions of 0.05%C, 0.5%Si, 1.0%Mn, 0.024%P. 0.002%S, 24.6%Cr and 19.3%Ni. The materials used contained 0.02, 0.05, 0.1, 0.2 and 0.5%Ti and all showed fully austenitic microstructures.

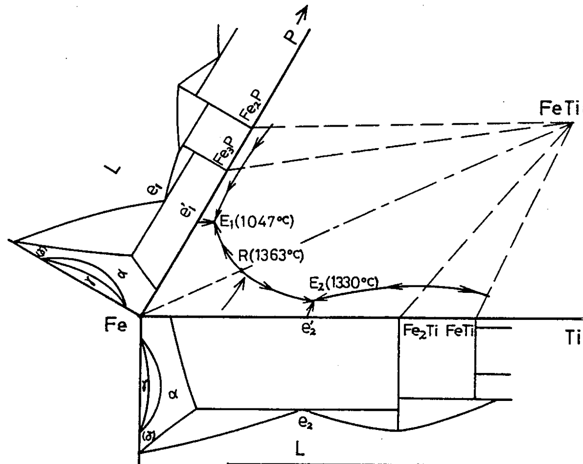
The cracking susceptibility of the materials was evaluated by the Trans-Varestraint test and three hot cracking tests. All testing procedures are the same as the previous report[10)].

4. Experimental Results and Discussion

4.1 Investigation of Fe-P-Ti ternary diagram and solidification temperature of phosphide

It was found that P was one of the most harmful elements to solidification crack susceptibility of commercial fully austenitic stainless steel weld metals, and the cause was attributed to low solidification temperatures of eutectics between austenite (γ) and M_3P phosphide[4),7),9)]. The means to raise the solidification temperature of phosphide would be of significance in improving cracking resistance. Therefore, several Fe-P-X ternary phase diagrams were investigated,[10)] and from such investigation Ti was expected to be a promising element.

Figure 3 shows schematically the Fe corner of the liquidus surface of Fe-P-Ti ternary phase diagram according to R. Vogel, et al.[16)] The curve $e_1'E_1$ is α-Fe-Fe_3P



	Fe(%)	P(%)	Ti(%)	Reaction
R	89.6	4.1	6.3	— — —
E_1	89.0	10.5	0.5	$E_1 \rightarrow \alpha_1 + Fe_3P + FeTiP$
E_2	85.3	0.7	14.0	$E_2 \rightarrow \alpha_2 + Fe_2Ti + FeTiP$
FeTiP	41.4	23	35.6	— — —

Fig. 3 Schematic liquius surface of Fe-P-Ti ternary phase diagram[16)].

binary eutectic line, the curve $e_2'E_2$ is α-Fe-Fe_2Ti binary eutectic line, and the curve E_1RE_2 is α-Fe-FeTiP binary eutectic line. Supposing that residual liquid varies in composition shown in Fig. 3 with a drop in temperature,[15)] compositional variation line of liquid intersects with the curve RE_2 and from the intersection the liquid varies with the solidification of α-Fe and FeTiP to the composition E_2 along the curve RE_2. When the compositional variation line intersects with the curve RE_1, the composition of the residual liquid varies to the composition E_1. If the liquid composition varies along the curve RE_2, the liquid solidifies at higher temperatures than the liquid solidifying along the curve RE_1. Therefore, the effect of Ti is expected when Ti addition can make residual liquid solidify to the composition R and subsequently along the compositional curve RE_2.

In the case of SUS 310S, however, the compositional variation of residual liquid, the composition of R point, the temperatures of eutectics, etc. are really different from those shown in Fig. 3, because primary solidification phase is austenite and other elements such as Cr, Ni, etc. are included. Thus the thermal analyses of SUS 301S type alloys containing intentionally considerable amount of P and Ti were performed by using crucibles. **Figure 4** shows the thermal analysis results of 23%Cr-

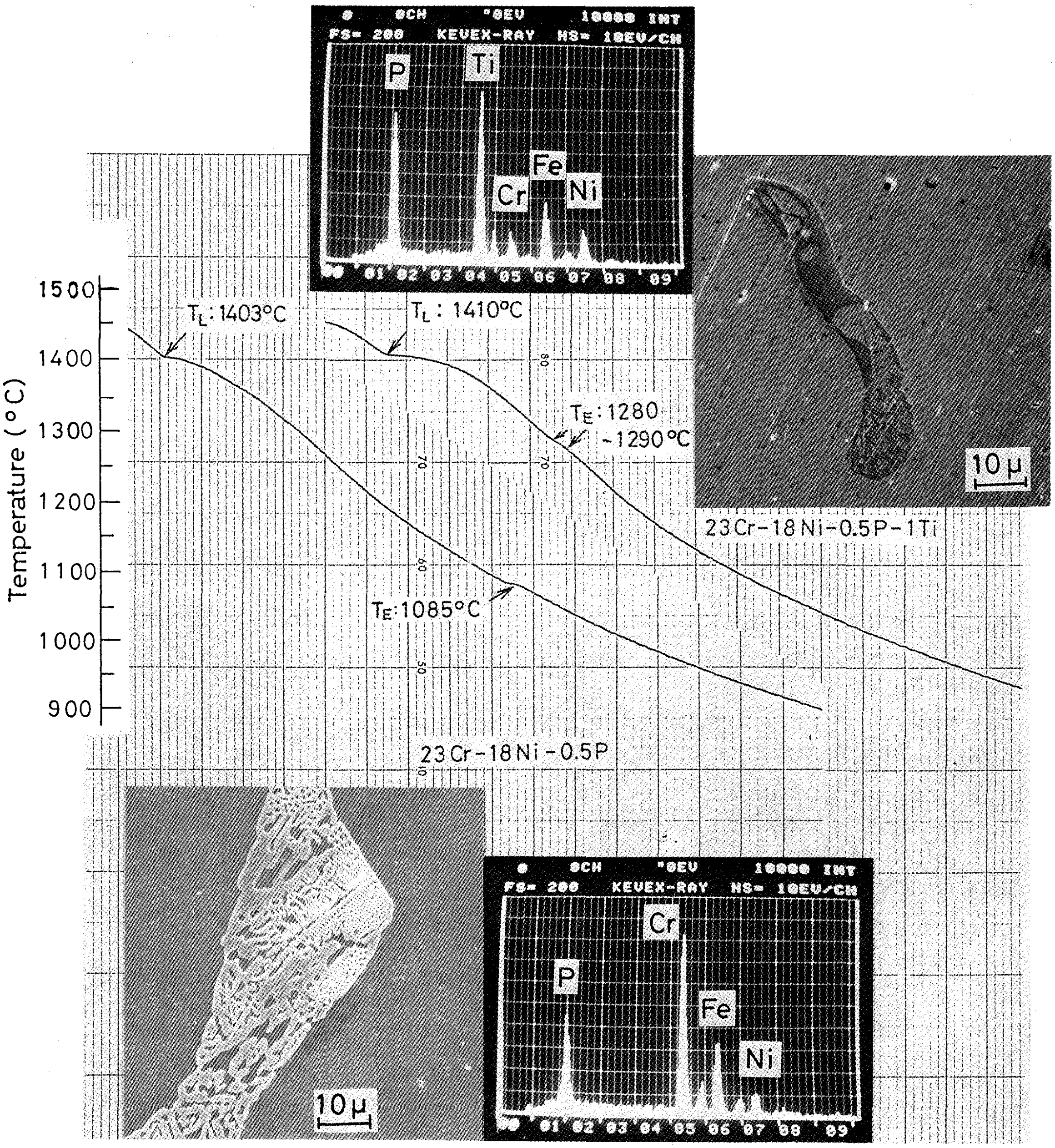


Fig. 4 Thermal analysis results, microstructures of phosphides and EDX results of phosphides in 23%Cr-18%Ni alloys containing 0.5%P-1%Ti and 0.5%P-0%Ti.

18%Ni alloys containing about 0.5%P and 1%Ti and 0.5%P and 0%Ti, together with the microstructures showing γ-phosphide eutectics and the EDX results of phosphides. The solidification temperature of γ-M_3P phosphide eutectic is about 1085°C, while the solidification temperature of γ-Ti phosphide eutectic is about 1280 to 1290°C which is about 200°C higher than the solidification temperature of γ-M_3P phosphide eutectic and moreover about 40°C higher than the lowest temperature of the BTR of commercially available SUS 310S which is shown in the mark △ in Fig. 2. It will be deduced that an optimum addition of Ti content to commercial SUS 310S can narrow the BTR and consequently reduce solidification crack susceptibility.

4.2 Effect of Ti addition on solidification crack susceptibility

Solidification crack susceptibility of alloys was first evaluated by the BTR obtained at an augmented-strain of about 4% by the Trans-Varestraint test.[7),18)] **Figure 5** shows the relationship between the BTR and the Ti content in SUS 310S with 0.024%P and 0.002%S. The

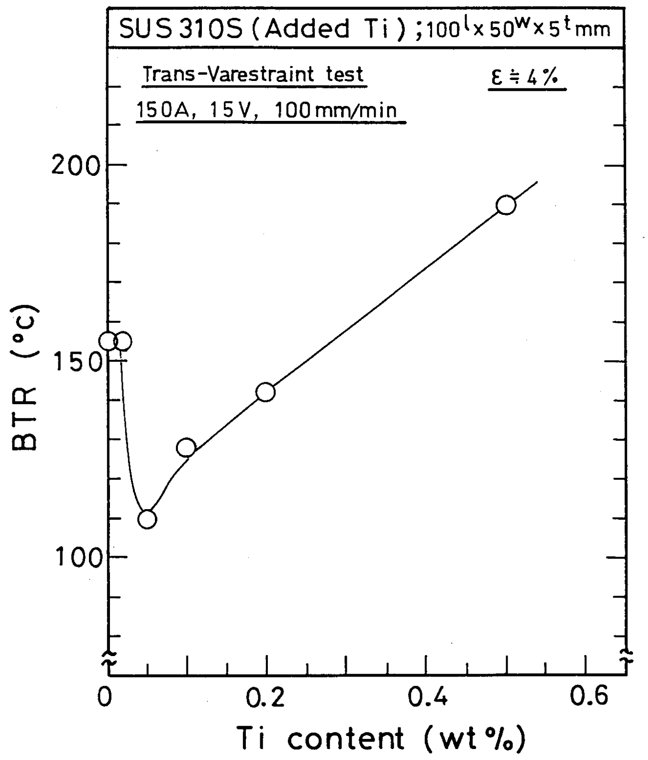


Fig. 5 Effect of Ti on BTR (at ϵ = 4%) of SUS 310S weld metals containing 0.024%P and 0.002%S.

BTR narrowed from 155°C for 310S down to 110°C at 0.05%Ti but increased to the contrary gradually from 110 up to 190°C with an increase in Ti content from 0.05 to 0.5%. The addition of 0.04 to 0.12%Ti could reduce the BTR to 130°C and less.

Subsequently, whether the optimum addition of Ti was beneficial in decreasing cracking in practical use was confirmed by performing the modified CPT(cast-pin tear) test and GTA spot and bead welding tests. The results are all indicated in **Fig. 6**. In the CPT test CR (Cracking ratio) decreased from 65% for SUS 310S to about 5% at 0.05%Ti. In GTA spot and bead welding tests no cracks were present at 0.05 and 0.1%Ti although total crack length of 2 and 2.5 mm were observed in SUS 310S weld metals. These results indicate that the cracking susceptibility was enhanced at 0.5%Ti on the contrary.

It was found from all the results that the addition of 0.04 to 0.12%Ti had a beneficial effect on the improvement of the solidification crack susceptibility of commercial SUS 310S.

The reason for the beneficial effect of Ti was investigated in terms of formed phases or inclusions in weld metals. **Figure 7** shows an example of the EDX result of microconstituent at solidification grain boundary in weld metal containing 0.05%Ti. It was found that microconstituents enriched in P, Ti, Cr, Fe, Ni, etc. were

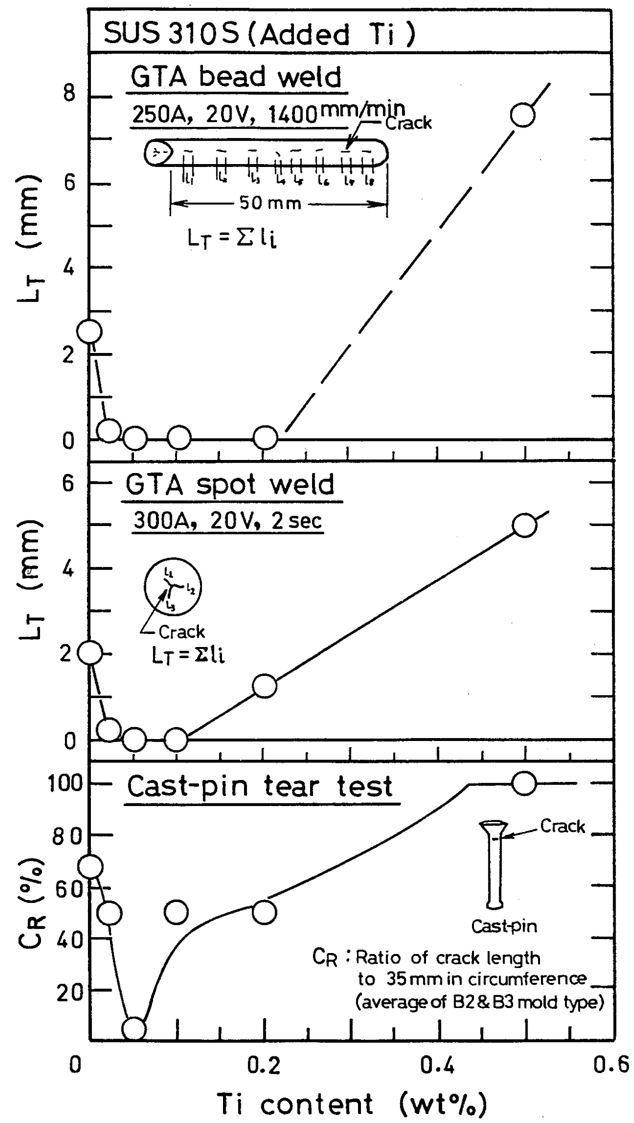


Fig. 6 Summary of effect of Ti on cracking propensity in modified CPT test and GTA spot and bead welding tests.

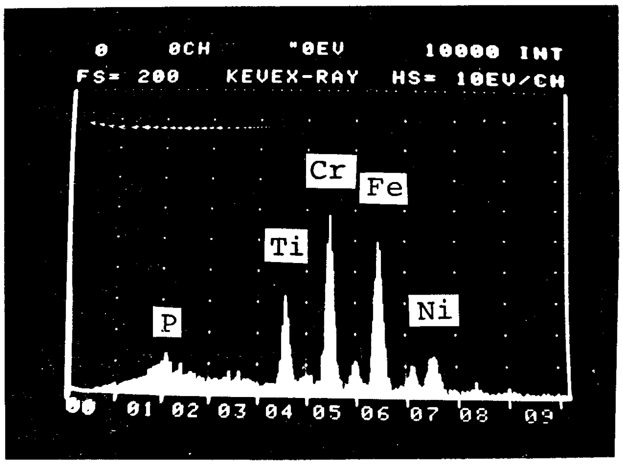


Fig. 7 EDX result of microconstituent at solidification grain boundary in SUS 310S weld metal containing 0.024%P, 0.002%S and 0.05%Ti, showing combination of P and Ti.

formed at 0.05%Ti in place of M_3P type phosphides. It is therefore postulated that the solidification temperature of these microconstituents is raised as compared with that of γ-M_3P phosphide eutectic, as expected from Fe-P-Ti ternary phase diagram in **4.1**. In other words, it is considered that the lesser cracking susceptibility is due to a rise in the melting point of liquid enriched in P.

In the case of an excessive Ti addition, a number of microconstituents enriched in Ti were detected at grain boundaries. It is thought that the melting point of them is so low as to enhance cracking susceptibility[10].

5. Conclusions

The effect of Ti on the cracking susceptibility of SUS 310S fully austenitic weld metals was studied by the BTR in the Trans-Varestraint test and cracking in practical hot cracking tests. The following conclusions can be drawn:

(1) It was revealed that a small amount of Ti addition had a beneficial effect in reducing cracking. In the case of 0.024%P and 0.002%S the effective Ti content was in the range of 0.04 to 0.12% and the optimum Ti content was about 0.05%.

(2) It was possible to obtain crack-free fully austenitic weld metals in GTA spot and bead welding.

(3) The beneficial effect of Ti addition was attributed to the raised solidification temperature of phosphide eutectics.

(4) On the contrary an excess of Ti addition was judged to be harmful to cracking. The detrimental effect was postulated to result from the increased amount of low melting point eutectics enriched in Ti.

References

1) H. Thielsch: Welding Journal, Vol. 29 (1950), No. 12, Research suppl., pp. 577-s–621-s.

2) J.C. Borland and R.N. Younger: British Welding Journal, Vol. 7 (1960), No. 1, pp. 22–60.

3) T.G. Gooch and J. Honeycombe: Metal Construction, Vol. 7 (1975), No. 3, pp. 146–148.

4) F. Matsuda, H. Nakagawa, S. Katayama and Y. Arata: Trans. of the Japan Welding Society, Vol. 13 (1982), No. 2, pp. 115–132.

5) Y. Arata, F. Matsuda and S. Saruwatari: Trans. of JWRI, Vol. 3 (1974), No. 1, pp. 79–88.

6) Y. Arata, F. Matsuda and S. Katayama: Trans. of JWRI, Vol. 5 (1976), No. 2, pp. 135–151.

7) Y. Arata, F. Matsuda and S. Katayama: Trans. of JWRI, Vol. 6 (1977), No. 1, pp. 105–116.

8) Y. Arata, F. Matsuda, H. Nakagawa and S Katayama: Trans. of JWRI, Vol. 7 (1978), No. 2, pp. 169–172.

9) F. Matsuda, S. Katayama and Y. Arata: Trans. of JWRI, Vol. 10 (1981), No. 2, pp. 201–212.

10) F. Matsuda, H. Nakagawa, S. Katayama and Y. Arata: Trans. of JWRI, Vol. 11 (1982), No. 1, pp. 79–94.

11) F. Matsuda, H. Nakagawa, S. Katayama and Y. Arata: Trans. of JWRI, Vol. 11 (1982), No. 2, pp. 79–85.

12) Y. Arata, F. Matsuda, H. Nakagawa, S. Katayama and S. Ogata: Trans. of JWRI, Vol. 6 (1977), No. 2, pp. 197–206.

13) F. Matsuda, H. Nakagawa, S. Ogata and S. Katayama: Trans. of JWRI, Vol. 7 (1978), No. 1, pp. 59–70.

14) F. Matsuda, H. Nakagawa, T. Uehara, S. Katayama and Y. Arata: Trans. of JWRI, Vol. 8 (1979), No. 1, pp. 105–112.

15) F. Matsuda, H. Nakagawa, S. Katayama and Y. Arata: Trans. of JWRI, Vol. 12 (1983), No. 1, pp. 89–95.

16) R. Vogel and B. Gießen: Archiv für das Eisenhüttenwesen, Vol. 30 (1959), No. 9, pp. 565–576.

17) T. Senda, F. Matsuda and H. Nakagawa: Journal of the Japan Welding Society, Vol. 42 (1973), No. 10, pp. 998–1006 (in Japanese).

18) T. Senda, F. Matsuda, G. Takano, K. Watanabe, T. Kobayashi and T. Matsuzaka: Journal of the Japan Welding Society, Vol. 41 (1972), No. 6, pp. 709–723 (in Japanese).