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Varestraint Test for Solidification Crack Susceptibility in Weld Metal of Austenitic Stainless Steels†

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Abstract

The Varestraint Test (Longitudinal Varestraint Test) was used to evaluate the susceptibility to hot cracking of ten commercial austenitic stainless steels (17 to 25 % Chromium and 8 to 20 % Nickel) which contain different amount of δ-ferrite in austenitic phase. As it is known from literatures or practical experiences, the austenitic stainless steels containing 5 to 10 % δ-ferrite at room temperature are more resistant to hot cracking than fully austenitic stainless steels.

The purpose of this investigation was to clarify the resistance to hot cracking in the weld metals and the HAZ that contain controlled amount of δ-ferrite as mentioned above, using the Varestraint Test.

Furthermore, the effect of nitrogen, which is a strong austenitizer, on hot crack susceptibility of weld metals was investigated. The authors found that the tendency of hot crack susceptibility of the weld metal and HAZ agreed with the order that has been described in the literatures and has been experienced in practical use, and that the weld metal became more susceptible to hot cracking when some amount of nitrogen was contained.

1. Introduction

The austenitic stainless steels have been widely used in petroleum, chemical, steam power and nuclear equipments, which are especially required to satisfy a number of requirements, such as corrosion and oxidation resistances, structural stability, strength and toughness under low and high temperatures or high pressure.

As far as welding is concerned, the austenitic phase has not a hardnability by rapid cooling and has a larger solubility for hydrogen than the ferrite phase, therefore so called "cold cracking" seldom occurs, but hot cracking which occurs during early time of solidification is the most troublesome. It is said that this is "solidification cracking"[1] or "super-solidus cracking"[2]. One of the most effective counterplans to decreasing solidification crack susceptibility is well known to control the δ-ferrite level in austenitic stainless steel weld metal.

Though the explanation of this reason has not yet reached satisfactorily, the validity of δ-ferrite on solidification crack susceptibility has been extensively recognized, so far, by means of cast pin tear test[3], finger test[4], murex test[5], circular-groove test[6], etc. This investigation was carried out to recognize the beneficial effect of controlled amount of δ-ferrite for commercial stainless steels using Varestraint Test.

Moreover the comparison of solidification crack susceptibility between weld metal and HAZ was investigated. Furthermore the effect of nitrogen, which is contaminated in shielding argon gas from air atmosphere or which is consciously added in base metal, on solidification crack susceptibility was discussed.

2. Experimental Procedure and Materials used

The chemical compositions of specimens used are shown in **Table 1.** Ten kinds of specimens used were commercial stainless steel plates which were produced by two different steel makers, A (simbol mark: A) and B (symbol mark : B).

All the test specimens for the Longitudinal Varestraint Test were machined and ground to 12 mm in thickness, 50 mm in width and 350 mm in length. For 12 mm plate thickness, the applied strain (augmented strain) was varied from 0.2 to 4.0 % by using the bending blocks of different radius. Test welding was performed by bead-on-plate welding of conventional TIG arc (DCSP) under pure Ar or Ar-N_2 (5 % and 20 %) shielding gases of 15 l/min. The welding conditions used show in **Table 2.** Subsequent to the Varestraint Test, the length of the longest crack, i. e., maximum length of crack, and the sum of each crack, i. e., total length of cracks, on the surface of test specimen was examined and measured at 40 × magnification in the as-welded condition and after polishing to the plate surface, it was etched by using nitrohydrochlolic acid reagent, then the microstructure of solidification crack was investigated.

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

JIS Code	Symbol	C	Si	Mn	P	S	Ni	Cr	Mo	Ti	Nb+Ta
SUS304	304-A	0.060	0.64	0.96	0.020	0.003	9.65	18.60	—	—	—
SUS304L	304L-A	0.017	0.56	1.09	0.025	0.010	10.40	18.48	—	—	—
SUS316	316-A	0.050	0.66	0.89	0.021	0.005	12.30	17.00	2.26	—	—
SUS316L	316-A	0.020	0.70	0.93	0.018	0.007	15.11	17.10	2.62	—	—
SUS321	321-A	0.060	0.58	1.03	0.027	0.007	9.48	17.69	—	0.44	—
SUS310S	310S-A	0.070	0.70	1.07	0.023	0.012	20.10	24.65	—	—	—
SUS304*	304-B	0.07	0.67	1.56	0.020	0.003	8.64	18.54	—	—	—
SUS316*	316-B	0.07	0.67	1.50	0.031	0.010	11.92	16.97	2.23	—	—
SUS316L*	316L-B	0.026	0.84	1.56	0.025	0.006	12.60	17.12	2.20	—	—
SUS347*	347-B	0.06	0.64	1.22	0.025	0.008	9.66	18.36	0.04	—	0.78

* materials used for supplemental test

Table 2. Welding and straining conditions for the Varestraint Test.

Welding condition	Augmented strain	Shielding gas
TIG, DCSP 250 A. 17 V. 10 cm/min 3.2 mmϕ, Th-W electrode	0.2 to 4.0 %	1) pure Ar gas: 15 l/min 2) Ar-5%N_2 gas: 15 l/min 3) Ar-20%N_2 gas: 15 l/min

3. Comparison of Crack Susceptibility of Commercial Austenitic Stainless Steels

3-1 Feature of Crack and Microstructure

The typical examples of cracking modes on weld metal surface of 316L-A stainless steel are shown in **Photo. 1 (a), (b), (c), (d)** and **(e)** at augmented strain levels of 0.5, 1.0, 2.0, 2.4 and 4.0 %, respectively.

When it exceeds the minimum augmented strain required to cause cracks, a small cracks originated near the fusion boundaries within the weld metal and appeared in the perpendicular direction to a molten ripple line at the instant the augmented strain applied. Subsequently, with an increase of augmented strain the number of cracks increased toward an inward location along the ripple line, and the length of each crack also increased as in (b) through (e). The longest crack at each augmented strain usually occurred near one-third in the width of weld bead.

In **Photo. 2 (a)** through **(f)** the appearances of typical cracks are compared for six weld metals at the same 4.0 % augmented strain. From Photo. 2 the grain size of columnar crystal seems to be the largest in 310S-A weld metal. The comparison of the solidification microstructures near the cracks in weld metals is done in **Photo. 3 (a)** through **(d).** The solidification microstructures of 304-A, 304L-A and 321-A which occur the relatively small cracks remarkably differ in those of 316L-A and 310S-A which occur the large cracks. The stems of cellular dendrites in 304-A. 304L-A and 321-A are finer in width and their secondary branches are well-developed and intertwined each other than those in 316L-A and 310S-A, and therefore the boundaries of columnar crystals as well as cellular dendrites were difficult to find out. This was indicated by one of the authors in the previous report[7].

Moreover the cracks propagated jaggedly along

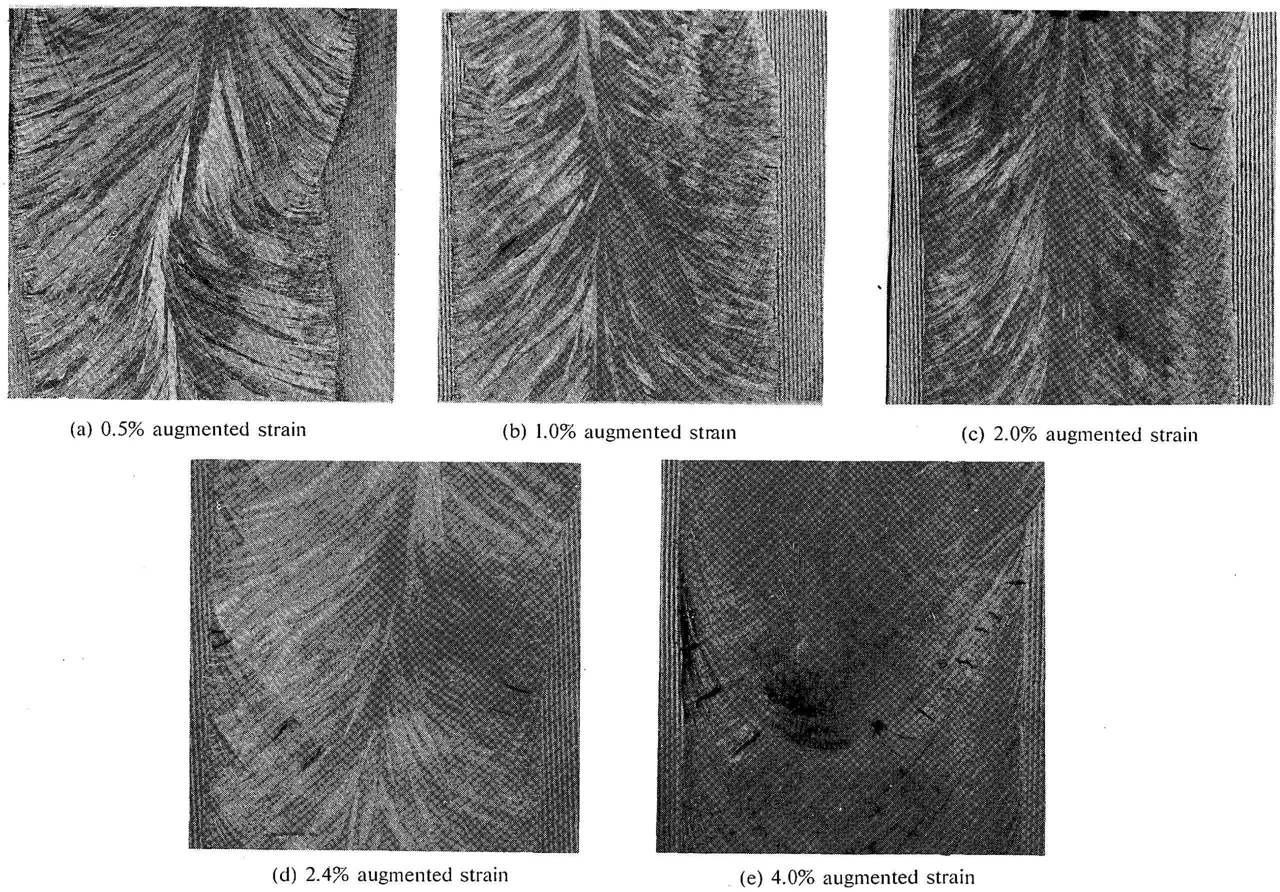


Photo. 1. Variation of cracking modes in weld metal with an increase of augmented strain for 316L-A stainless steel.

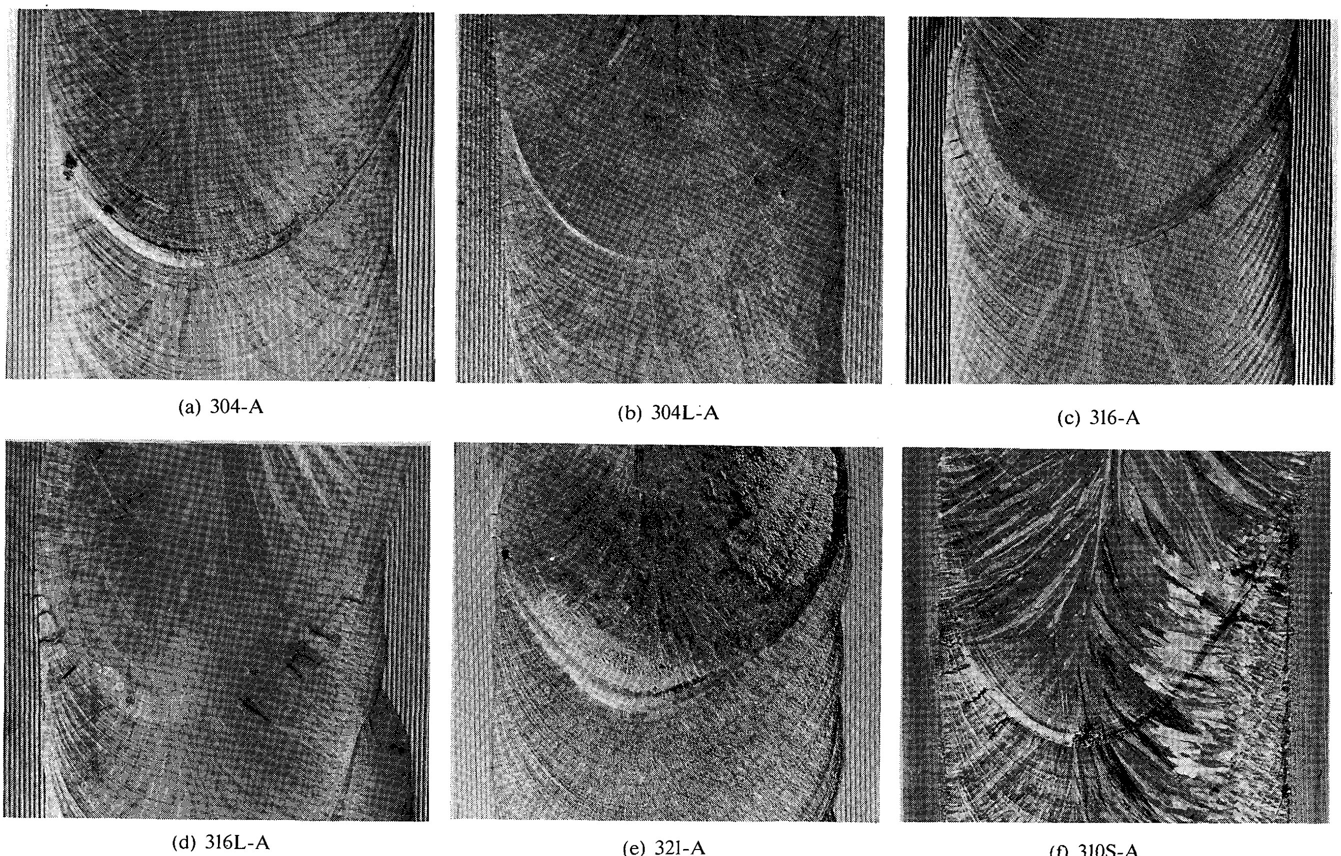
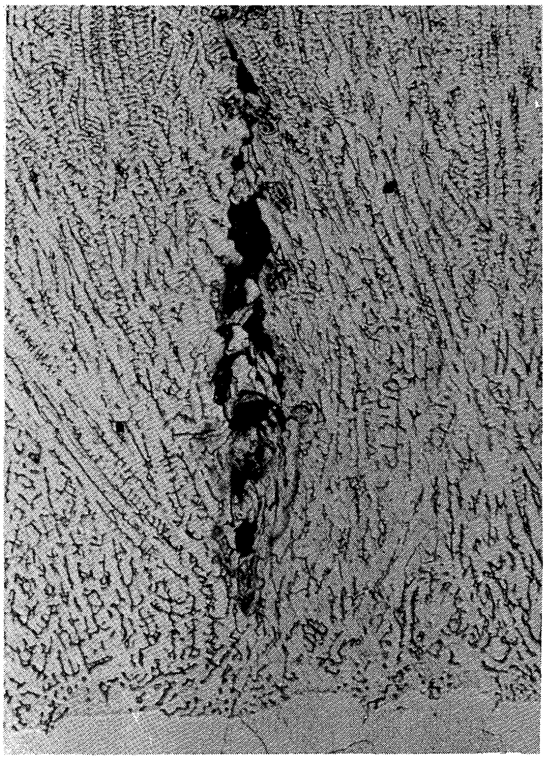
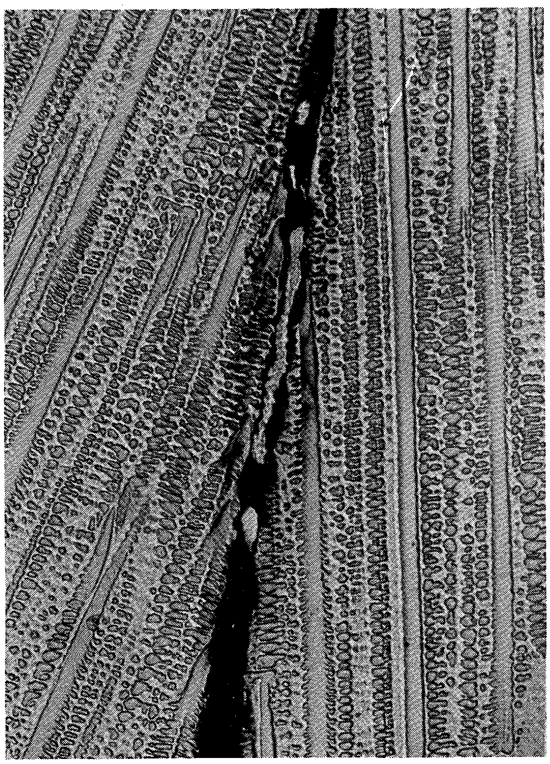


Photo. 2. Comparison of cracking modes on weld metal surfaces of austenitic stainless steels which were tested with 4.0% augmented strain.

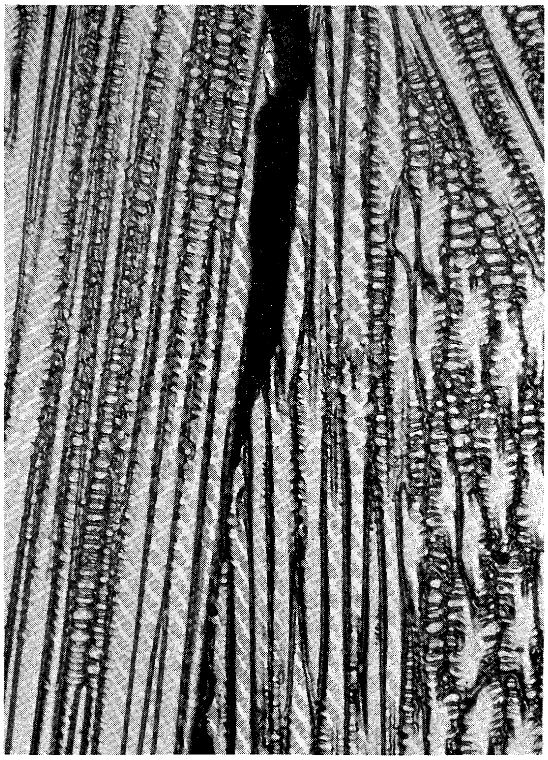


(a) 304-A containing δ-ferrite (×150)

(b) 321-A containing δ-ferrite (×150)



(c) 316L-A of fully austenitic phase (×150)

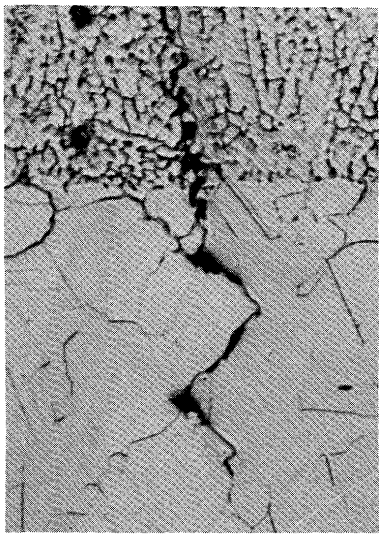


(d) 310S-A of fully austenitic phase (×150)

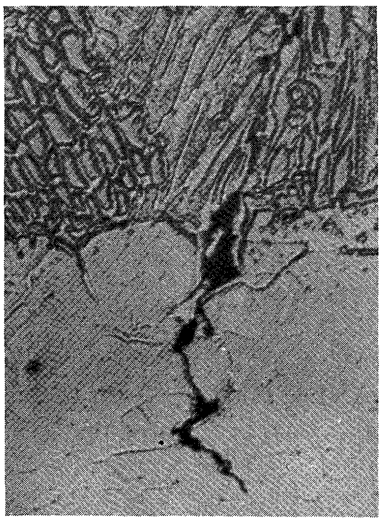
Photo. 3. Comparison of microstructures and cracking modes in weld metal of austenitic stainless steels which were tested with 4.0% augmented strain.

the intricate boundaries in 304-A, 304L-A and 321-A weld metals. In 316L-A and 310S-A weld metals, it is easy to find out the boundaries of columnar crystals as well as cellular dendrites. The large cracks occur along those boundaries of columnar crystals.

Photo. 4 (a) and **(b)** show so called "liquation cracking" in HAZ near fusion boundary in 4 % augmented strained specimen of 304-A and 316-A, respectively. The comparison of susceptibility to cracking was made for weld metal and HAZ near fusion boundary, that is, each minimum augmented strain required to cause cracking was shown in **Fig. 1** on an average of two or three specimens of each stainless steel. Black and white arrow represent the minimum augmented strain required to cause cracking



(a) 304-A (×150)



(b) 316-A (×150)

Photo. 4. Example of liquation cracking in HAZ near fusion boundary.

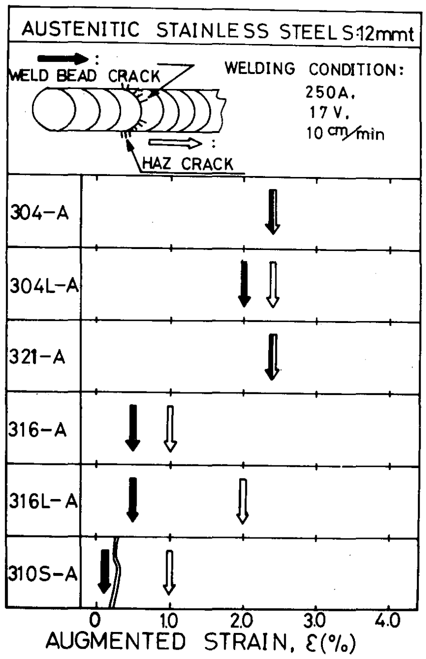


Fig. 1. Minimum augmented strain required to cause cracking for weld metal and HAZ of each austenitic stainless steel.

for the weld metal and the HAZ, respectively. In Fig. 1 the weld metal which was melted by TIG arc without filler metal corresponds to so called "Unmixed Zone" by Szekeres[8] in case of actual welding and the HAZ near fusion boundary corresponds to so called "Partially Melted Zone".

As a result, it is clear that in 304L-A, 316-A, 316L-A and 310S-A, the weld metal (unmixed zone) is more susceptible to the initiation of cracking than the HAZ (partially melted zone), although the two regions show almost the same in 304-A and 321-A.

Moreover it is shown that the minimum augmented strain to cause cracking for the weld metal and the HAZ is generally lower in 316-A, 316L-A and 310S-A than that in 304-A, 304L-A and 321-A. However the crack susceptibility in the HAZ of 316L-A is considerably lower than other two 316-A and 310S-A. From the result of Fig. 1 the authors have mainly treated about the cracking in the weld metal.

3-2 maximum Length of Crack

The effect of the augmented strain on the maximum length of crack, L_M, is shown in **Fig. 2** for weld metals of these stainless steels. The minimum augmented strain required to cause cracking in weld metals was less than 0.2 % for 310S-A, at 0.5 % for 316-A and 316L-A, at 2.0 % for 304L-A and at 2.4 % for 304-A and 321-A. Subsequently each curve increased to the maximum length as the augmented strain increased to a critical value and then continued the maximum length irrespective of

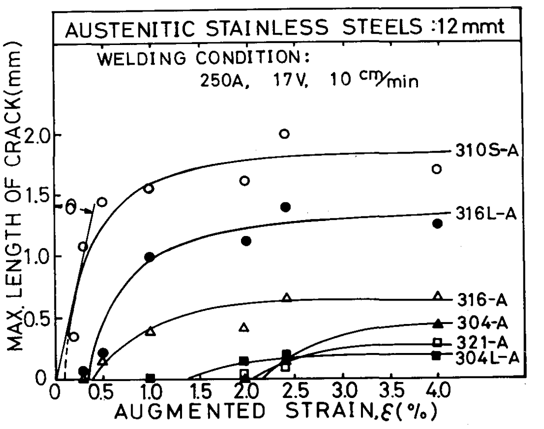


Fig. 2. Effect of augmented strain on maximum length of crack for weld metal of each austenitic stainless steel.

more increasing of augmented strain. The maximum length is shown at about 1.0 % augmented strain for 310S-A, about 1.5 % for 316-A and 316L-A, about 2.0 % for 304L-A, and about 4.0 % for 304-A and 321-A.

From these maximum values it is suggested that the brittleness range for solidification cracking exists only within a certain temperature difference for each stainless steel. In comparison with these six stainless steels, it is obvious that solidification crack susceptibility of commercial stainless steels is remarkably different, and also can be easily compared with the Varestraint Test.

3-3 Total Length of Cracks

Most papers[7), 9), 10)] concerning the Varestraint Test have regarded the total length of cracks as one of the most important indices for evaluation of solidification crack susceptibility of steels. Therefore the total length of cracks, L_T, was also measured for all specimens tested in this investigation.

Fig. 3 shows the relation between the total length of cracks and augmented strain for weld metals of

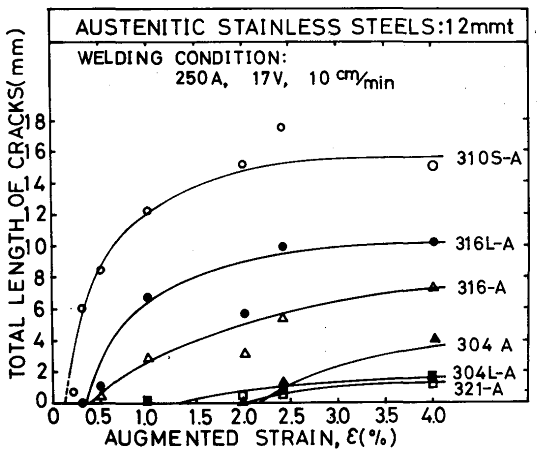


Fig. 3. Effect of augmented strain on total length of cracks for weld metal of each austenitic stainless steel.

these stainless steels. It is clear from the result of Fig. 3 that the solidification crack susceptibility of these stainless steels significantly differs each other as well as the relation for the maximum length of crack. Then the order of the crack susceptibility in Fig. 3 is almost the same as the maximum length of crack, that is, 310S-A, 316L-A, 316-A, 304-A and 304L-A and 321-A at 4 % strain level. Moreover the saturation of the total length of cracks occurs at about 2.0 % for 310S-A and 316L-A, at 2.4 to 4.0 % for 316-A, 304-A, 304L-A and 321-A.

3-4 Comparison of the Index CSS for Crack Susceptibility

One of the authors[7), 9)] has proposed from the result of the Varestraint Test that the indices CST• and CSS represent the reasonable solidification crack susceptibility. The value of CSS is calculated by $v \times \tan\theta$, where $\tan\theta$ is determined by the inclination of the tangential line to the maximum length of crack as shown in Fig. 2 and v is welding speed in mm/sec.

This value represents the critical strain rate required to cause cracking during solidification of weld metal. The values of CSS were determined from Fig. 2 for all weld metals. There are 4.6×10^{-3} (1/sec) for 310S-A, 16×10^{-3} for 316L-A, 39×10^{-3} for 316-A, 142×10^{-3} for 304-A, 242×10^{-3} for 321-A and 250×10^{-3} for 304L-A. The order of the CSS is the same as the orders of the maximum length of crack in Fig. 2 and the total length of cracks in Fig. 3 at 4 % augmented strain. The determination for the values of CSS of many steels is usually troublesome, and moreover it is difficult to obtain such a large quantity of steel when it is manufactured by experimental heat.

Therefore, for the purpose of doing a quick judgment on solidification crack susceptibilities of these stainless steels, the comparison of the maximum length of crack or the total length of cracks at 4 % augmented strain may be adopted. The same fact was seen in HY-type steels[9)]. However the authors would recommend the adoption of the total length of cracks instead of the maximum length of crack in case of the Longitudinal Varestraint Test because of the fluctuation of the data.

Nextly the authors investigated the supplemental test for comparison with the difference between the maximum length of crack obtained by the Longitudinal and the Transverse Varestraint Tests at augmented strain of 4.0 %.

Consequently the length of the maximum cracks of the two type Varestraint Tests was almost the same as shown in **Table 3.** Therefore, the maximum length of crack is convertible between the two Varestraint Tests at augmented strain of 4 %.

Table 3. Relation between the maximum length of cracks (mm) obtained by the Longitudinal and the Transverse Varestraint Tests (4 % augmented strain).

Symbol	Longi. type	Trans. type
316-B	1.35	1.15
316L-B	0.50	0.72
310S	2.03	2.18
430*	0.74	0.71

* Ferritic stainless steel as a reference

4. Effect of δ-Ferrite on Solidification Crack Susceptibility

4-1 For Commercial Austenitic Stainless Steels

The effect of δ-ferrite has been described in the many papers[3), 4), 6), 7), 11), 12), 13), 14), 15)] that the solidification crack susceptibility of fully austenitic stainless steels is considerably improved by containing δ-ferrite of a few percents. Therefore the amount of δ-ferrite at room temperature in these weld metals by TIG arc bead-on-plate welding was measured by the ferrite scope and the ferrite indicator. The result was shown in **Table 4.** The relations between the amount of δ-ferrite and the maximum and the total length of cracks at 4 % augmented strain and the value of CSS were studied in these stainless steels as shown in Table 4.

Consequently the order of the maximum or the total length of cracks was reversely proportional to the order of the amount of δ-ferrite, that is, the higher the δ-ferrite content is, the less susceptibility to the solidification crack of stainless steels becomes. These results also suggest that the BTR (brittleness temperature range) is largely different according to the variations of δ-ferrite content in these stainless steels. From the above facts, it is clarified that δ-ferrite in austenitic stainless steel weld metals provides the beneficial effect on the susceptibility to solidification crack. Note that the solidification microstructures were different between fully austenitic 310S-A and 316L-A, and 304-A, 304L-A and 321-A containing δ-ferrite.

The microstructures of the latter were intertwined in appearance in comparison with those of the former. The authors think that there is some relation between the features of the microstructures and the crack susceptibility.

Table 4. δ-ferrite content, maximum and total length of cracks at 4 % augmented strain and CSS values for each stainless steel.

Symbol	δ-ferrite content (%)	L_M(mm)	L_T (mm)	CSS (1/sec)
304-A	3.9	0.44	3.9	142×10^{-3}
304L-A	8.3	0.15	1.5	250×10^{-3}
316-A	1.7	0.63	7.4	39×10^{-3}
316L-A	0	1.25	10.1	16×10^{-3}
321-A	6.5	0.27	1.4	242×10^{-3}
310S-A	0	1.60	14.9	4.6×10^{-3}
304-B	8.0	0.16	0.5	—
316-B	0.8	1.35	10.3	—
316L-B	3.3	0.50	6.8	—
347-B	7.0	0.46	5.4	—

4-2 Effect of Nitrogen on Solidification Crack Susceptibility

Nitrogen is known to be a strong austenitizer. Delong[13] proposed the new constitution diagram which was corrected the schaeffler constitution diagram for austenitic stainless steel weld metals. In the new constitution diagram the nickel equivalent was modified by addition of a nitrogen factor.

In this section, therefore, the effect of nitrogen in weld metal on solidification crack susceptibility was investigated. As the method of nitrogen addition to weld metals, argon gas mixed with nitrogen of 5 and 20 % was used as shielding gas of TIG arc welding.

Fig. 4 shows the change of the nitrogen gas content (wt %) in the weld metals after welding under Ar shielding gas with and without N_2 gas.

The relation between the amount of δ-ferrite content which was measured by the ferrite indicator and nitrogen content in weld metals is shown in **Fig. 5** for each stainless steel. As a result, the higher the N content is, the less the amount of δ-ferrite in case of

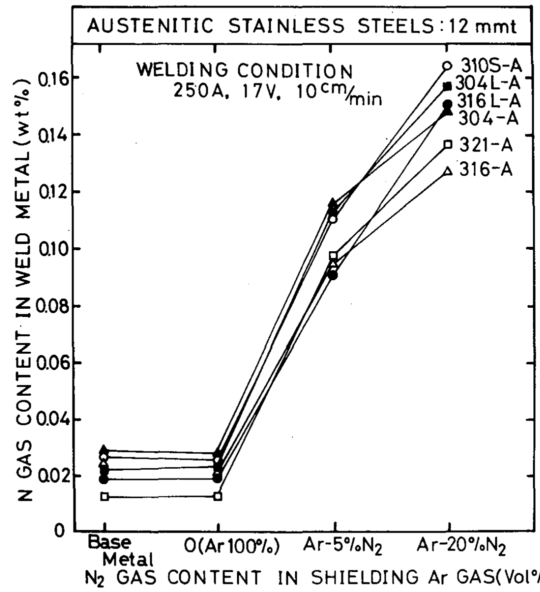


Fig. 4. Nitrogen content in weld metals of austenitic stainless steels which were welded under Ar-N_2 atmosphere.

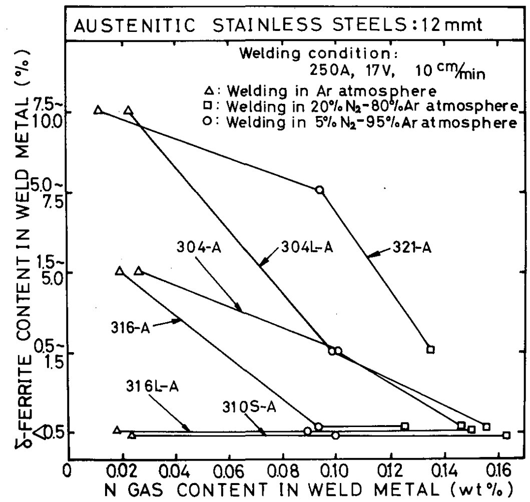


Fig. 5. Effect of nitrogen on δ-ferrite content for weld metals of austenitic stainless steels.

321-A, 304L-A, 304-A and 316-A becomes, and in the weld metal containing 0.15 % of nitrogen, δ-ferrite almost disappears for these steels. However the tendency of decreasing δ-ferrite is delayed in 321-A which contains titanium element of a strong nitride former.

In 310S-A and 316L-A which are fully austenitic stainless steels, the effect of δ-ferrite was not detected.

Photo. 5 shows the typical examples of the change of solidification microstructure of 304-A and 304L-A, respectively, which were welded in a pure Ar shielding gas for (a) and (c), and in Ar-20%N_2 shielding gas for (b) and (d). In case of the Ar atmosphere, it has the fine and intertwined solidification microstructures in which δ-ferrite is seen as mentioned in 3-1. However in case of Ar-20%N_2 atmosphere, it has the coarse solidification microstructures which are the same mode as those of 310S-A and 316L-A as shown in Photo. 3 (c) and (d), that is, it is clear to convert the characteristic solidification microstructure which appears in fully austenitic phase.

Figs. 6 and **7** show the relations between the maximum length of crack and the total length of cracks, and the N_2 gas content in shielding Ar gas, respectively. As shown in broken lines in both

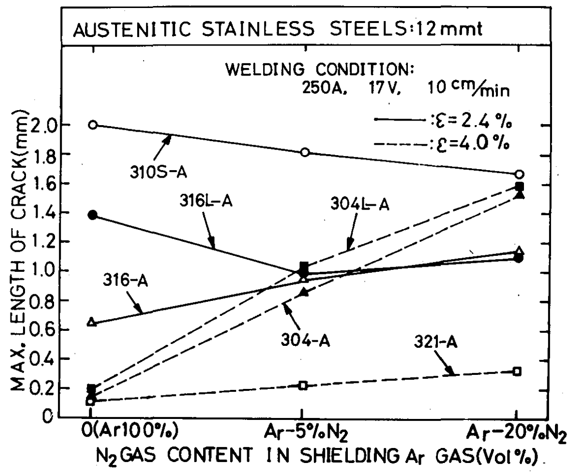
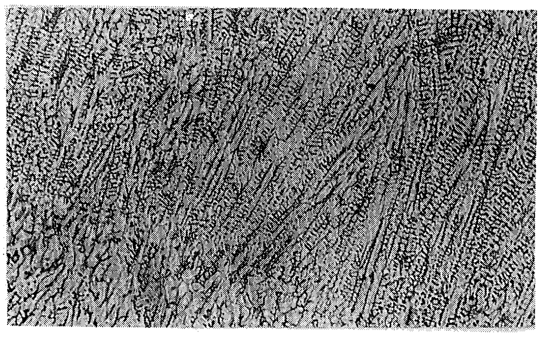
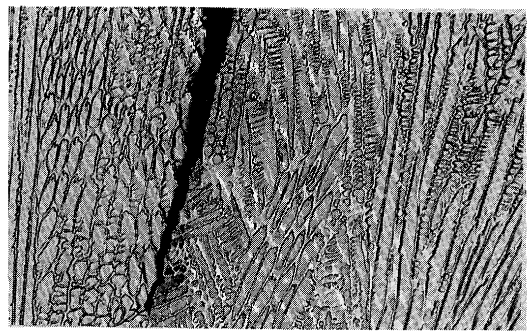


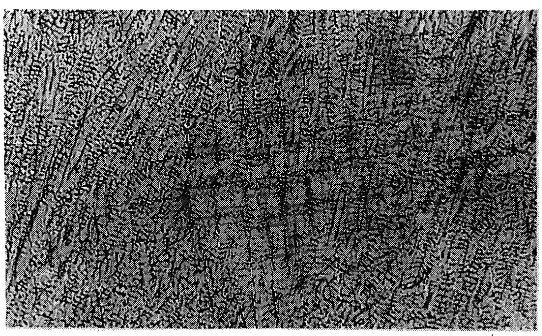
Fig. 6. Variation of maximum length of crack in weld metals which were welded under Ar-N_2 atmosphere.



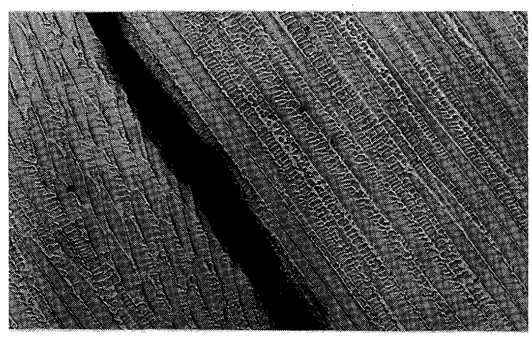
(a) 304-A welded under Ar shielding gas (×150)



(b) 304-A welded under Ar-20%N_2 shielding gas (×150)



(c) 304L-A welded under Ar shielding gas (×150)



(d) 304L-A welded under Ar-20%N_2 shielding gas (×150)

Photo. 5. Comparison of cracking modes and microstructures in weld metals which were welded under Ar shielding gas with and without nitrogen gas.

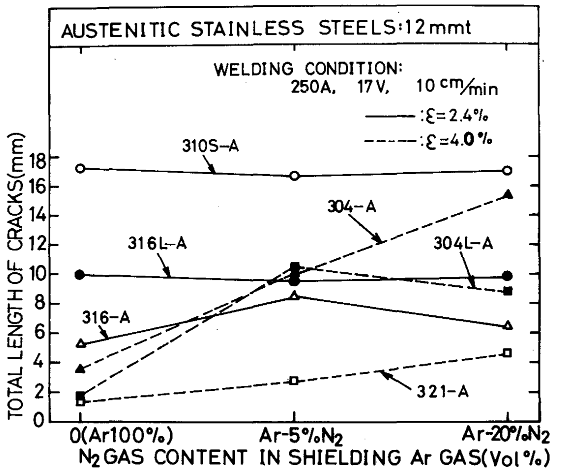


Fig. 7. Variation of total length of cracks in weld metals of austenitic stainless steels which were welded under Ar-N_2 atmosphere.

figures, the maximum length of crack and the total length of cracks of 304-A, 304L-A and 321-A increased with an increase of N_2 gas content. This is due to decrease of the amount of δ-ferrite. However as shown in solid lines, these parameters of 310S-A and 316L-A of fully austenitic phase showed approximately constant values in both figures.

Fig. 8 collectively shows the relations between the amount of δ-ferrite in weld metal and the maximum length of crack and the total length of cracks at 4 % augmented strain level. Although some fluctuations of data are seen at 0 % of δ-ferrite, mostly the solidification crack susceptibilities of weld metals for austenitic stainless steels are shown by the solid lines

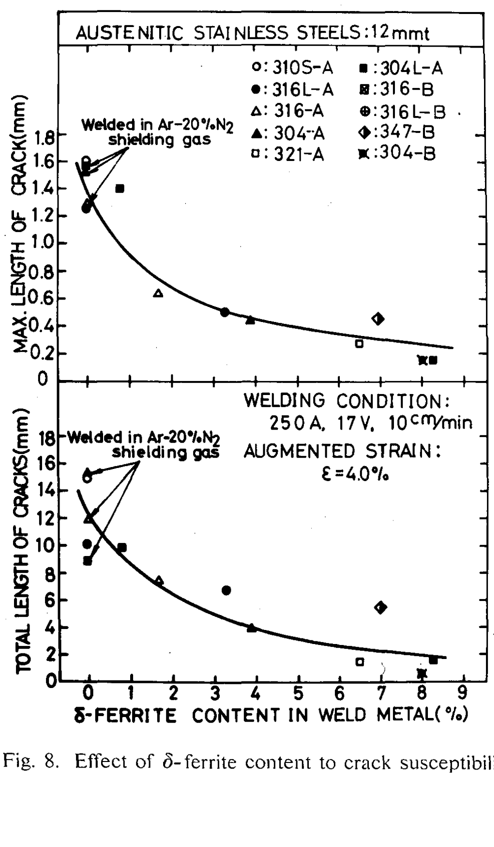


Fig. 8. Effect of δ-ferrite content to crack susceptibility.

in the figure. Judging from Fig. 8 the values of two parameters show almost the same in the range more than 4 to 5 % of δ-ferrite. As a result, the beneficial effect of δ-ferrite on solidification crack susceptibility is quantitatively proved in this report, which were widely said in the many lieteratures.

5. Conclusions

Solidification crack susceptibilities for weld metals of various commercial austenitic stainless steels were investigated in this report using the Varestraint Test. The main conclusions obtained are as follows:

(1) The crack susceptibility of the weld metals with bead-on-plate TIG arc welding is usually worse than that of the HAZ. Therefore it seems from this result that the unmixed zone in actual welding is more susceptible to cracking than the partially melted zone near fusion boundary.

(2) The crack susceptibility for the weld metals of austenitic stainless steels used is placed in order of good quality as 304L-A and 321-A, 304-A, 316-A, 316L-A and 310S-A. This order is also supported by the CSS index. The maximum length of crack and the total length of cracks at 4 % augmented strain can substitute for the CSS index which is the most reasonable representation with respect to the solidification crack susceptibility.

(3) The solidification crack susceptibility for austenitic stainless steels is strongly depended on the amount of δ-ferrite in austenitic phase. More than 4 to 5 % of δ-ferrite after welding improves considerably the crack susceptibility of austenitic stainless steels. Decreasing δ-ferrite in austenitic phase increases the crack susceptibility.

(4) The solidification microstructures show different modes between the weld metals which are insusceptible to cracking as 304-A, 304L-A and 321-A, and which are susceptible to cracking as 316-A, 316L-A and 310S-A, that is, in the former the substructures are intertwined and the boundaries of the columnar crystals are difficult to find out, but in the latter the boundaries of the columnar crystals are clear. The authors think that the difference of the crack susceptibility between them is considerably related to the variation of the microstructural mode. The relation between the variation of the microstructure and the solidification crack susceptibility is not crear and is in future work.

(5) The addition of nitrogen to the weld metals which contain δ-ferrite in austenitic phase changes the microstructure to fully austenitic phase. Therefore

the crack susceptibility of weld metals containing δ-ferrite also gradually increases with an increase of nitrogen. In this experiment the weld metals of 321-A, 304L-A and 316-A were applicable to this case. Therefore, it should be noted in welding of stainless steels that mixing of air in shielding gas of pure argon makes the solidification crack susceptibility worse.

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