Title	Effect of Oxygen Content on Cold Cracking Susceptibility in Weld Metal of High Strength Steel(Materials, Metallurgy & Weldability)
Author(s)	Matsuda, Fukuhisa; Nakagawa, Hiroji; Shinozaki, Kenji et al.
Citation	Transactions of JWRI. 1985, 14(2), p. 335-342
Version Type	VoR
URL	https://doi.org/10.18910/8617
rights	
Note	

Effect of Oxygen Content on Cold Cracking Susceptibility in Weld Metal of High Strength Steel†

Fukuhisa MATSUDA*, Hiroji NAKAGAWA**, Kenji SHINOZAKI*** and Takeshi MATSUMOTO****

Abstract

The purpose of this investigation is to make clear the effects of oxygen on cold cracking susceptibilities in weld metals of high strength steels. Therefore, in this study, cold cracking susceptibilities in weld metals of HY130 steel where oxygen content changes in the range 15–210 ppm were evaluated and then, in particular, the metallurgical characteristics in weld metal such as solidification behavior, microstructure, inclusion, formation and migration of austenite boundary etc. were systematically studied.

Consequently, cold cracking susceptibility and intergranular fracture in weld metal increased with an increase in oxygen content. The cause of this result was inferred that many inclusions which were related to diffusible hydrogen were situated near prior-austenite boundary, because inclusions crystallizing on solidification boundary hindered the migration of austenite boundary.

KEY WORDS: (Cold Cracking Susceptibility) (Oxygen) (Weld Metal) (High Strength Steel) (SMA Welding) (GTA Welding) (Solidification) (Inclusion)

1. Introduction

It was previously reported[1] by the authors that cold cracking susceptibility in weld metal of HY-type steel such as HY110, HY130 etc. was severer than in HAZ and intergranular fracture in weld metal easily occurred by SMA welding rather than by GTA welding.

It is generally known that the materials where intergranular fracture easily occurs have high susceptibility to cold cracking[2),3] and oxygen content in weld metal by SMA welding is essentially high. These references suggest two questions about those experimental results, that is to say, (i) Why does oxygen assist intergranular fracture? and (ii) Is SMA welding suitable for ultra-high strength steels?.

Microstructure in weld metal is different from that in HAZ, because weld metal has solidification structure. As for different points, for example, (i) it has directional crystals. (ii) It has microsegregation. (ii) It has many small inclusions. The effects of these characteristics in weld metal on cold cracking are unknown now.

Therefore, in particular, behaviors of oxygen and grain boundary during and after solidification, that is to say, the metallurgical characteristics in weld metal such as solidification behavior, microstructure, inclusion, formation and migration of austenite boundary etc. were systematically studied in order to make clear the effects of oxygen on cold cracking susceptibilities.

2. Materials Used and Experimental Procedure

2.1 Materials used

Base metal used was weldable heat-treated high strength steel, HY130 whose nominal ultimate strength was 100 kgf/mm^2. Filler wire named F(130) was used for automatical GTA welding and well matched with base metal in strength level. Designation, type of chemical composition, yield strength and ultimate strength of HY130 used were shown in the previous report.[4]

2.2 Cold cracking test

Cold cracking susceptibility in weld metal was discuss-

† Received on October 31, 1985

* Professor
** Research Instructor
*** Research Associate, Faculty of Engineering, Osaka University
**** Graduate Student (Presently, Nisshin Steel Co., Ltd.)

Transactions of JWRI is published by Welding Research Institute of Osaka University, Ibaraki, Osaka 567, Japan

ed by the lower critical stress (LCS) obtained by the LB-TRC test.[5)] In the LB-TRC test, weld bead was laid by GTA welding with argon gas containing oxygen and hydrogen in order to change oxygen content in weld metal, systematically. Four combinations of oxygen and hydrogen gases in argon gas were selected in order to get variable oxygen content and constant diffusible hydrogen content as shown in **Table 1**. Consequently, oxygen contents in weld metal changed in 15, 30, 60 and 210 ppm, respectively, but diffusible hydrogen contents in various shielding gases were approximately constant. The GTA welding conditions used were welding current of 300 A, arc voltage of 14 V and welding speed of 120 mm/min, respectively. Testing procedure was the same as the previous report.[4)]

Table 1 Diffusible hydrogen and oxygen contents in weld metal using various combinations of hydrogen, oxygen and argon mixing gas as shielding gases

Mixing ratio (%)		Diffusible hydrogen content (ml/100g)	Oxygen content (ppm)
H_2	O_2		
3.2	0.0	9.7	15
2.0	0.5	8.2	30
1.0	1.0	7.9	60
0.35	3.0	8.0	210

3. Experimental Result and Discussion

3.1 Effect of oxygen content on lower critical stress and fracture surface

3.1.1 Lower critical stress

Figure 1 shows the comparison of LCS in GTA weld metal with in SMA weld metal in various steels under the same diffusible hydrogen levels using the LB-TRC test. The lower critical stresses in both weldings reduce with increasing in hardness, but that in SMA weld metal is lower than in GTA weld metal regardless of the same diffusible hydrogen levels. It is predicted that this result is due to the difference of oxygen content in both weldings. Therefore, the effect of oxygen content on LCS was systematically studied in HY130 weld metal using the LB-TRC test. The relation between applied stress and fracture time in various oxygen levels is shown in **Fig. 2**. Though the differences of LCS among various shielding gases are small because of higher diffusible hydrogen contents, LCS reduces and fracture time becomes shorter with an increase in oxygen content, clearly. This result suggests that oxygen makes LCS reduce, that is to say, oxygen makes cold cracking susceptibility in weld metal increase.

3.1.2 Fracture surface

Fracture surfaces were observed in order to clear the effect of oxygen on LCS. **Figure 3** shows macrofractographs in weld metal in oxygen contents of 15, 30, 60 and 210 ppm using the LB-TRC test. Fracture stresses in these specimens are in the range 26–30 kgf/mm^2.

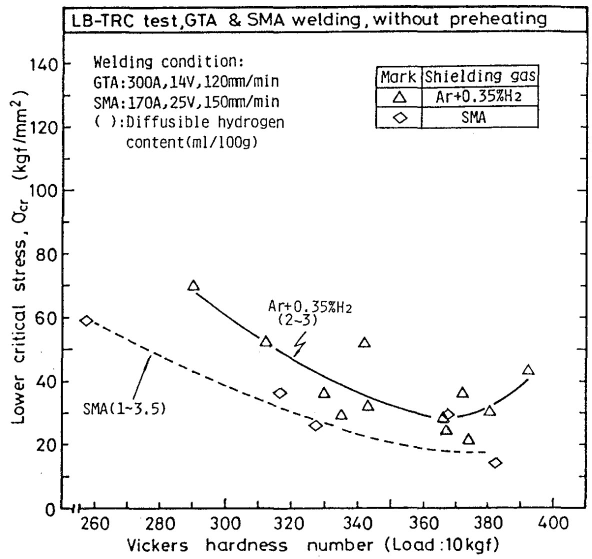


Fig. 1 Comparison of lower critical stress in GTA weld metal with in SMA weld metal

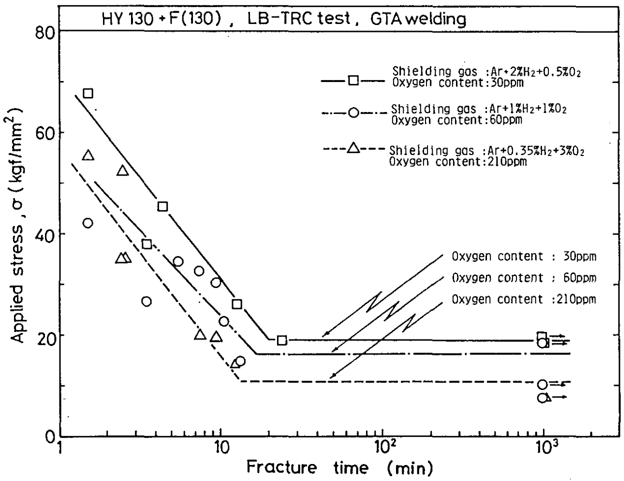
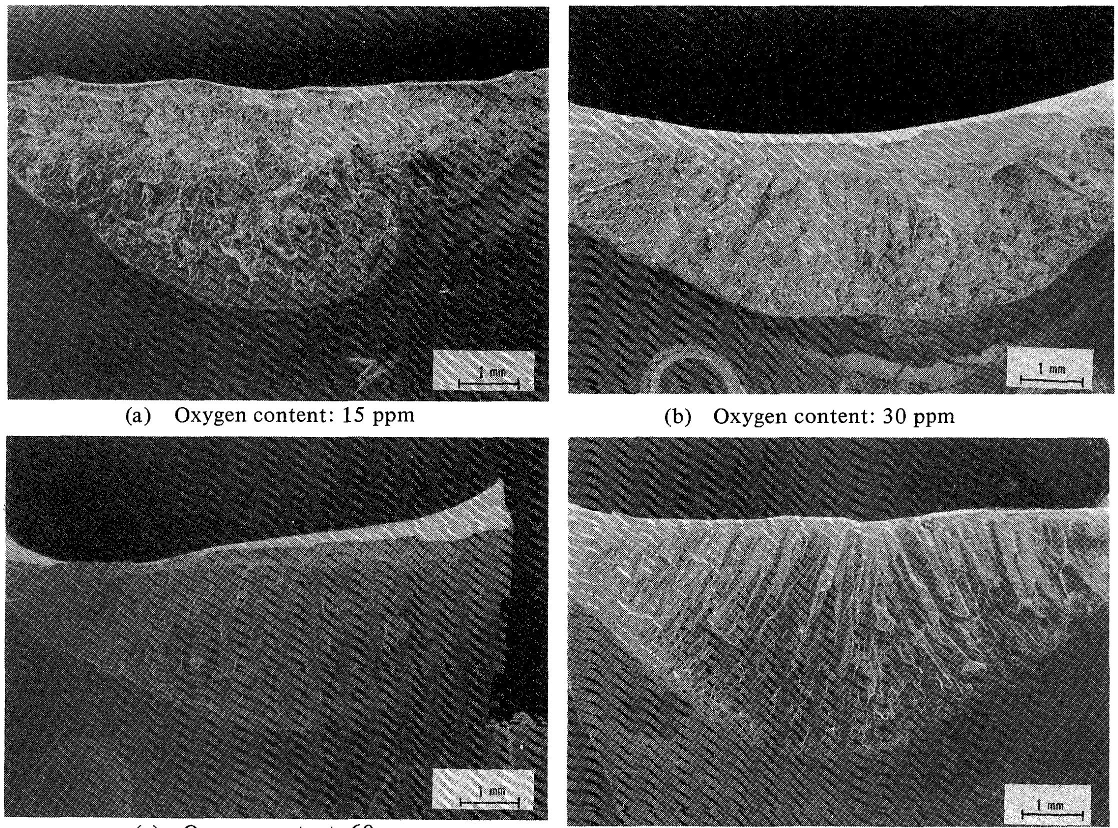


Fig. 2. Effect of oxygen content in weld metal on lower critical stress and fracture time in the LB-TRC test

Fracture surfaces were mainly occupied by intergranular fracture along columnar crystal (IG_c^W), quasi-cleavage fracture (QC_c^W) and shear lips (D^W), microscopically. IG_c^W and QC_c^W regions were mainly observed at the root where crack initiated. D^W was observed at bead surface. Fracture surface in oxygen content of 15 ppm was mainly occupied by QC_c^W region, but that in oxygen content of 210 ppm was mainly occupied by IG_c^W region. As it seemed that IG_c^W region spread with an increase in oxygen content in the weld metal, the area fractions of IG_c^W region in all specimens were measured. Measuring method was described as follows; About 10–12 fields (118 × 86 mm) magnified by a scanning electron microscope of 300 magnifications were inspected from cold crack region and then the areas of intergranular fracture regions in various fields were measured by point counting method. The area fractions of



(a) Oxygen content: 15 ppm (b) Oxygen content: 30 ppm

(c) Oxygen content: 60 ppm (d) Oxygen content: 210 ppm

Fig. 3 Effect of oxygen content in weld metal on macrofractograph of root crack in weld metal in the LB-TRC test

IG_c^W region was defined by the ratio of cumulative area of intergranular fracture regions in various fields to total area of fields.

The relation between applied stress and the area fraction of IG_c^W region in various oxygen contents were summarized in **Fig. 4 (a)**, **(b)**, **(c)** and **(d)**. IG_c^W region reduces with an increase in applied stress in all figures. This tendency can be easily understood by Beachem's theory.[6] The relation between oxygen content in weld metal and the area fraction of IG_c^W region in the applied stresses of 20, 30 and 40 kgf/mm^2 was shown in **Fig. 5** obtained by curves in Fig. 4. IG_c^W regions in various stress levels increase like a parabolic curve with an increase in oxygen content. In particular, these rapidly increase up to about oxygen content of 60 ppm in various stress levels. Moreover, fracture surface in oxygen content of 210 ppm had the same feature as that in SMA weld metal which has been previously shown.[1]

It was inferred from this result that reducing of LCS with an increase in oxygen content was due to increasing of intergranular fracture region. Therefore, metallurgical investigations were carried out in order to make clear the reason why intergranular fracture easily occurred in the weld metal containing oxygen.

3.2 Effects of oxygen content on various metallurgical factors

3.2.1 Intergranular fracture

Firstly, intergranular fracture surfaces were observed in detail. Intergranular fracture surfaces in oxygen contents of 15, 60 and 210 ppm are shown in **Fig. 6 (a)**, **(b)** and **(c)**. In oxygen content of 15 ppm, many directional secondary cracks and tear ridges which are related to the direction of lathes of martensite are seen on intergranular fracture surface. This feature indicates that if it has a chance, crack propagates lath boundary of martensite rather than grain boundary. In oxygen content of 60 ppm, secondary cracks almost change to microvoids and do not have directionally appearance. Moreover, inclusions were usually seen in microvoids. In oxygen content of 210 ppm, secondary cracks almost disappear and many micro-voids which often line are observed on intergranular fracture surface. As for another feature, plastic deformations were never seen around micro-voids and micro-projections named micro-cones well matched with micro-voids. As it seems that there are many micro-voids on intergranular fracture surface in higher oxygen level rather than in lower oxygen level, change of micro-voids and micro-cones vs. oxygen content is measured as shown in **Fig. 7**. Micro-voids and micro-cones increases like a palabolic curve with an increase in oxygen content. This tendency of increment of micro-voids and micro-cones agrees with that of increment of intergranular

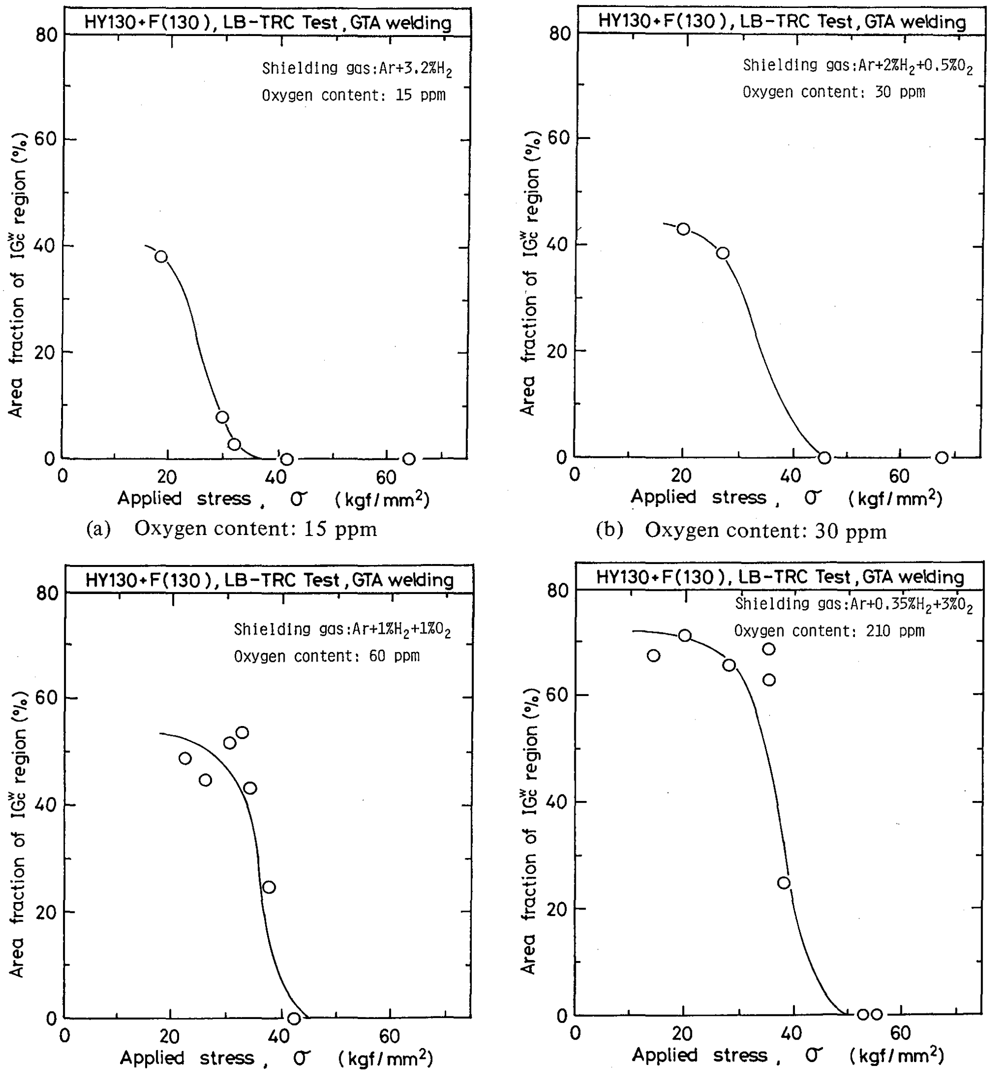


Fig. 4 Relation between applied stress and area fraction of IG_c^W region

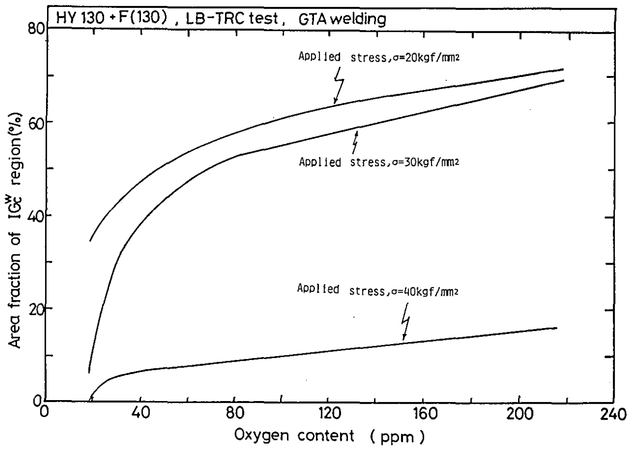
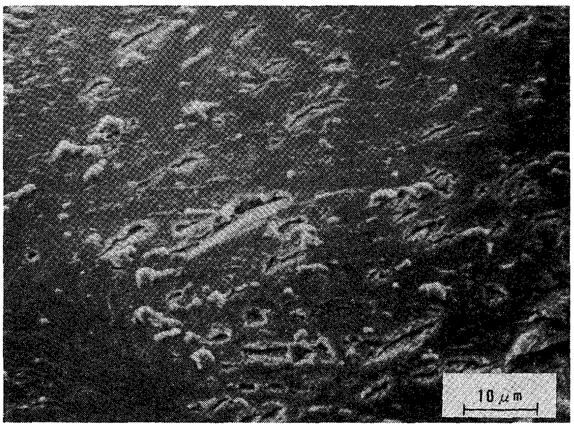


Fig. 5 Effect of oxygen content in weld metal on area fraction of IG_c^W region for several applied stresses in the LB-TRC test

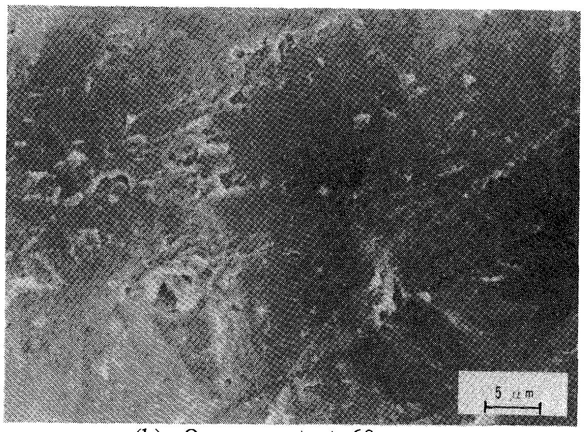
fracture region shown in Fig. 5. This result shows that occurrence of intergranular fracture is related to micro-voids and micro-cones on fracture surface. As inclusions were usually included in micro-voids, the relation between grain boundary and inclusions was observed. The number of inclusions within 2 μm apart from prior-austenite boundary of 160 μm long were measured in lightmicrophotographs magnified in 800 magnifications, because depth of micro-voids on fracture surface was less than about 2 μm. **Figure 8** shows the change of inclusion within 2 μm apart from prior-austenite boundary on oxygen content. Inclusions near grain boundary really increase with an increase in oxygen content like the curve in Fig.7. It is inferred from these results that intergranular fracture is affected by inclusions near prior-austenite boundary.

3.2.2 Inclusion

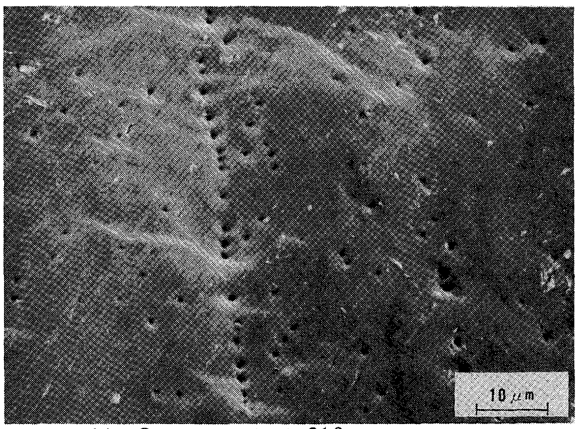
It is known that as solubility of oxygen in solid iron is so small, oxides mainly crystallize during solidifing. Therefore, inclusions described in the above seem to be mainly oxides. It is important to know the site where inclusion crystallizes in order to clear the relation between inclu-



(a) Oxygen content: 15 ppm



(b) Oxygen content: 60 ppm



(c) Oxygen content: 210 ppm

Fig. 6 Variation of intergranular fracture surface of weld metal with oxygen content in weld metal

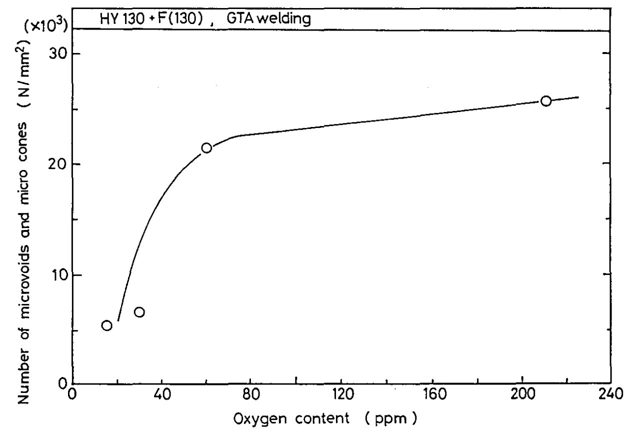


Fig. 7 Relation between oxygen content in weld metal and number of micro-voids and micro-cones on intergranular fracture surface

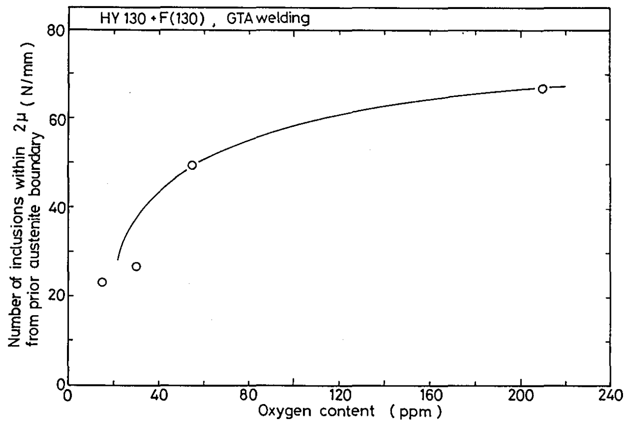


Fig. 8 Relation between oxygen content in weld metal and number of inclusions within 2 μm from prior-austenite boundary

sion and prior-austenite boundary.

Figure 9 shows the relation between oxygen content and number of inclusions situated on cellular dendrite boundary and in cellular dendrite. Number of inclusions more than 0.2 μm dia. was measured in lightmicrophotograph (80 × 120 mm) magnified in 800 magnifications. Inclusions situated in cellular dendrite are proportional to oxygen content, but those situated on cellular dendrite boundary rapidly increase up to oxygen content of about 60 ppm and then gradually increase with an increase in oxygen content. The difference of increasing in inclusions situated on cellular dendrite boundary and in cellular dendrite vs. oxygen content is not clear. However, this result shows that the density of inclusion situated on cellular dendrite boundary is much higher than that in cellular dendrite.

On the other hand, immediately after solidification completeted, austenite boundary coincided with solidification boundary. Moreover, solidification boundary is equal to cellular dendrite boundary. Considering these

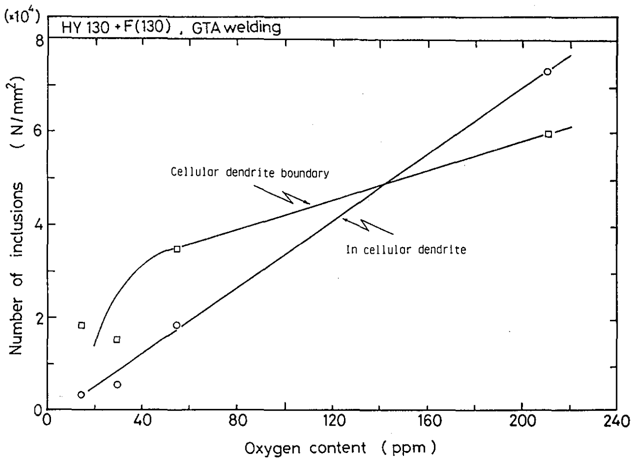


Fig. 9 Relation between oxygen content in weld metal and number of inclusions situated on cellular dendrite boundary and in cellular dendrite

results, it is inferred that the relation between inclusions and prior-austenite boundary in Fig. 8 is decided by the relation between prior-austenite boundary and solidification boundary.

It is generally known that as solidification boundary migrates with reducing of temperature in weld metal, grain boundary at room temperature migrates from solidification boundary. **Figure 10** shows the relations between oxygen content and frequency in agreement of prior-austenite boundary with solidification boundary, mean of grain boundary migration and mode of grain boundary migration. The volume of grain boundary migration was defined as the average of the shortest distance between solidification boundary and prior-austenite boundary. It was measured in lightmicrophotograph magnified in 500 magnifications. From this figure, the volume of grain boundary migration reduces with an increase in oxygen content up to oxygen content of about 60 ppm and then it is so little more than oxygen content of 60 ppm.

Judging from the above mentioned, it is inferred that as inclusions crystallizing on solidification boundary increase with an increase in oxygen content in weld metal,

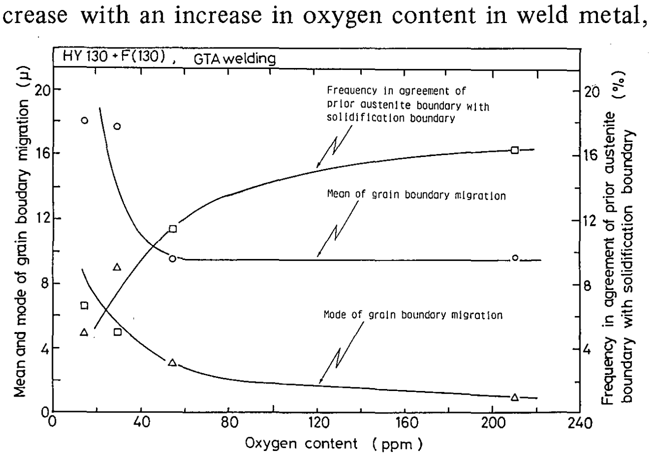


Fig. 10 Effect of oxygen content in weld metal on grain boundary migration

prior-austenite boundary is difficult to migrate from solidification boundary in higher oxygen content because of the pinning effect of these inclusions. Consequently, it seems that there are many inclusions near prior-austenite boundary in higher oxygen content.

3.2.3 Microstructure

It is important to know the effect of oxygen content on microstructure, because intergranular fracture is strongly affected by it. Lightmicrophotographs in oxygen contents of 15, 30, 60 and 210 ppm are shown in **Fig. 11 (a)**, **(b)**, **(c)** and **(d)**. In oxygen content of 15 ppm, it is obviously lath martensite structure in which packet and block defined by Marder[7] are observed. In oxygen contents of 30 and 60 ppm, they are still lath martensite structures. However, in oxygen content of 210 ppm, packet is never seen and it looks like accicular structure rather than like lath structure. This photographs may suggest that inclusion stopped growing of lathes.

3.2.4 Grain boundary segregation

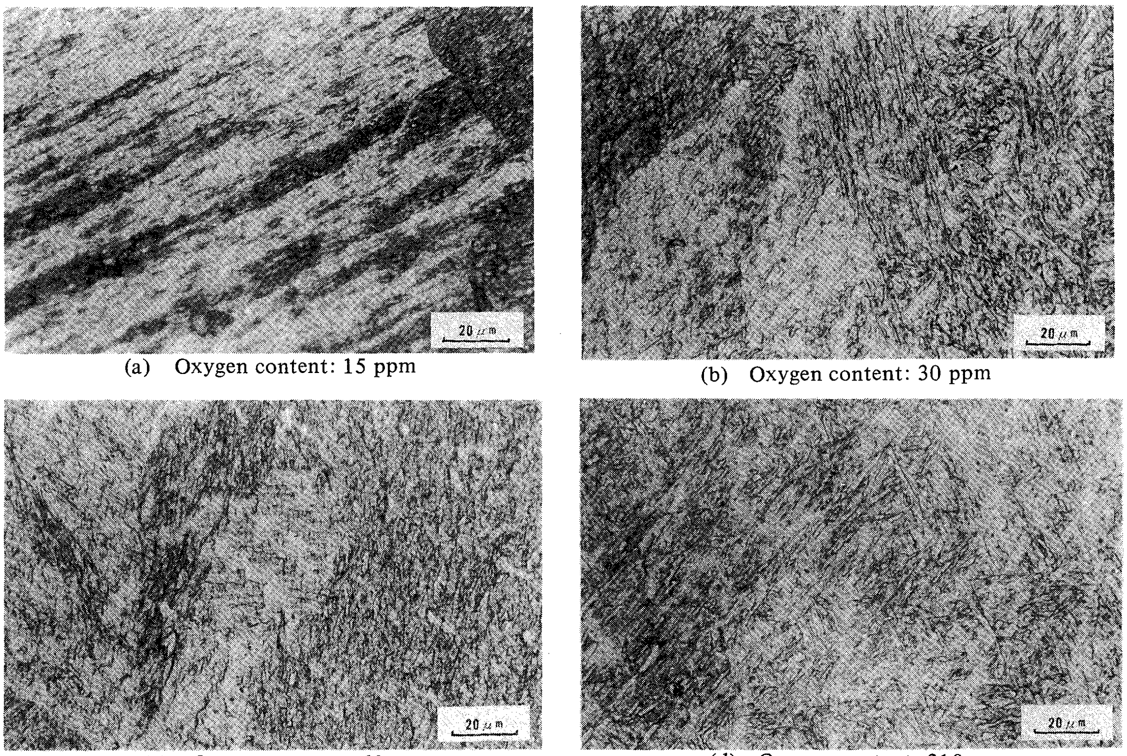
As oxygen segregating on prior-austenite boundary during cooling enabled to cause intergranular fracture, it was measured by Auger Electron Spectrometer (AES).

Figures 12(a) and **(b)** show AES spectrums obtained on intergranular and transgranular fracture surfaces in oxygen content of 210 ppm, respectively. Oxygen peak on intergranular fracture surface is much higher than that on transgranular fracture surface. From this result, it is obvious that oxygen segregates and oxide exists on prior-austenite boundary. **Figure 13** shows the relation between oxygen content and the relative peak height between oxygen peak at 503 eV and iron peak at 703 eV obtained on intergranular and transgranular fracture surfaces. Oxygen on transgranular fracture surface slightly increases with an increase in oxygen content, but oxygen on intergranular fracture surface is approximately constant regardless of oxygen content. It is inferred that the volume of oxygen segregating on prior-austenite boundary in oxygen content of 15 ppm is larger than that in oxygen content of 210 ppm, because number of inclusions situated on intergranular fracture surface in oxygen content of 15 ppm is much smaller than those in oxygen content of 210 ppm.

3.3 Discussion

As described in the above, there were three effects of oxygen on microstructure. That is to say, (i) Increment of grain boundary segregation of oxygen, (ii) Increment of oxides on grain boundary and (iii) Change of microstructure. The most effective factor among these for occurrence of integranular fracture was discussed hereafter.

It is said[8-10] that temper embrittlement and reheat cracking are affected by grain boundary segregation of impurity elements such as phosphorus and sulphur. Moreover, it is reported[3] that the susceptibility of hydrogen



(a) Oxygen content: 15 ppm (b) Oxygen content: 30 ppm

(c) Oxygen content: 60 ppm (d) Oxygen content: 210 ppm

Fig. 11 Effect of oxygen content in weld metal on microstructure at room temperature.

embrittlement in HY130 steel increases because of grain boundary segregation of silicon and nitrogen. However, judging from Fig. 13, it is inferred that the volume of grain boundary segregation of oxygen in oxygen content of 15 ppm is larger rather than that in oxygen content of 210 ppm. This result suggests that grain boundary segregation of oxygen doesn't strongly affect intergranular fracture.

Recently, it is reported[11] that lath structure changes to accicular feritic structure with an increase in oxygen content in weld metal, because ferrite easily precipitates on inclusion. In fact, microstructure in oxygen content of 210 ppm was accicular structure as shown in Fig. 11. This morphology may suggest that quasi-cleavage fracture induced by hydrogen easily occurs. However, lath martensite structure obviously observed in the oxygen content range 30–60 ppm where intergranular fracture rapidly increased. This result suggests that the change of microstructure doesn't mainly cause increase in intergranular fracture.

From experimental results, the change of intergranular fracture vs. oxygen content agreed with the change of inclusion on grain boundary vs. oxygen content. It is generally known[12),13] that hydrogen evolution rate is late in weld metal, because interface between inclusion and matrix is the site where hydrogen is temporally trapped. Moreover, it is reported[14] that when carbides precipitate on grain boundary, intergranular fracture easily occurs. Considering these experimental results and references, the reason why intergranular fracture increase and cold cracking susceptibility increase with an increase in oxygen content in weld metal is inferred that many inclusions where hydrogen is temporally trapped and then hydrogen embrittlement easily occurs are situated near prior-austenite boundary, because inclusions crystallizing on solidification boundary hindered the migration of austenite boundary.

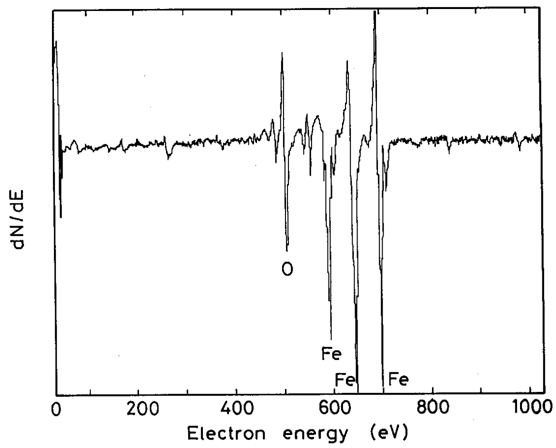
The experimental result suggests that as regards developing weld metal for high strength steels, not only hydrogen but also oxygen must be reduced.

4. Conclusion

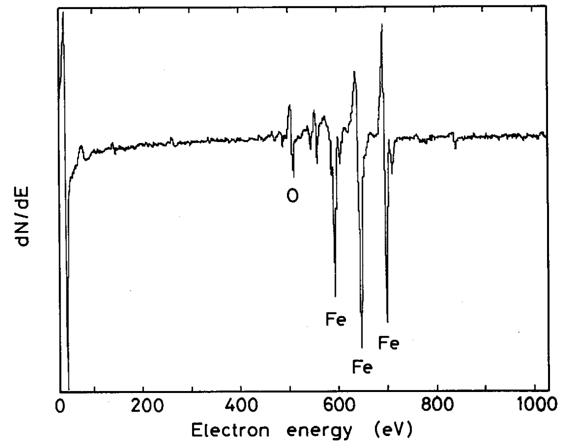
In this study, metallurgical characteristics in weld metal such as microstructure, inclusion, the relation between austenite boundary and solidification boundary, grain boundary segregation were observed in order to make clear the effects of oxygen content on cold cracking susceptibility in weld metal of HY 130 steel.

Main conclusions obtained are as follows.

1) Cold cracking susceptibility in weld metal increased with an increase in oxygen content and at the same time intergranular fracture surface did, too.
2) Intergranular fracture surface including oxygen had many micro-voids and micro-cones. There were many inclusions near prior-austenite boundary. These inclusions caused micro-voids and micro-cones on inter-



(a) Intergranular fracture surface



(b) Transgranular fracture surface

Fig. 12 AES spectrums obtained on intergranular and transgranular fracture surfaces in weld metal in oxygen content of 210 ppm

granular fracture surface.

3) Migration of austenite boundary from solidification boundary reduced with an increase in oxygen content, because inclusions crystallizing on solidification boundary hindered it.

4) Grain boundary segregation of oxygen in oxygen content of 15 ppm was approximately equal to that of 210 ppm obtained by Auger Electron Spectrometer.

5) Considering these experimental results, the reason why intergranular fracture increased with an increase in oxygen content in weld metal and at the same time, cold cracking susceptibility did was inferred that

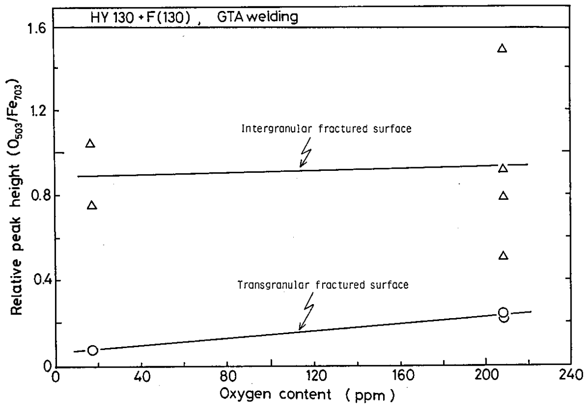


Fig. 13 Relation between oxygen content in weld metal and relative peak height of oxygen obtained on intergranular and transgranular fracture surfaces

many inclusions which were related to diffusible hydrogen were situated near prior-austenite boundary, because inclusions crystallizing on solidification boundary hindered the migration of austenite boundary.

Therefore, the experimental result suggests that as regards developing weld metal for high strength steels, not only hydrogen but also oxygen must be reduced.

References

1) F. Matsuda et al.: Trans. of JWRI, **6** (1977) 2, 59–73.
2) F. Nakazato et al.: Tetsu to Hagane, **61** (1975) 6, 67–81 (in Japanese)
3) C.L. Briant et al.: Metal. Trans., **19A** (1978) 5, 625–633.
4) F. Matsuda et al.: Trans. of JWRI, **9** (1980) 1, 87–92.
5) F. Matsuda et al.: Trans. of JWRI, **8** (1979) 1, 113–119.
6) C.D. Beachem: Metal. Trans., **3** (1972) 2, 437–451.
7) J.M. Marder et al.: Trans. ASM, **62** (1969) 1, 1–10.
8) H. Ikawa et al.: J. of JWS, **47** (1978) 7, 30–36 (in Japanese).
9) T. Fujii et al.: Tetsu to Hagane, **67** (1981) 9, 117–126 (in Japanese).
10) M.P. Seah et al.: Surface Sci., **53** (1975), 168–212.
11) Y. Kikuta et al.: J. of JWS, **50** (1981) 1, 19–28 (in Japanese).
12) G.M. Evans et al.: J.I.S.I., **207** (1969) 11, 1484–1490.
13) J. Moreton et al.: Metal. Const. and Brit. Weld. J., **3** (1971) 6, 223–228.
14) M. Hasegawa et al.: Tetsu to Hagane, **59** (1973) 14, 85–94 (in Japanese).