Flux-cored Wire for HT610 Class Steel Showing Excellent Toughness after PWHT

Dr. Yoshihiko KITAGAWA*1, Shuji SASAKURA*1, Masahiro INOMOTO*2, Hidenori NAKO*2, Yoshitomi OKAZAKI*2

*1 Welding Process Department, Technical Center, Welding Business
*2 Materials Research Laboratory, Technical Development Group

A detailed study has been conducted to improve notch toughness after post weld heat treatment (PWHT) of weld metal made from flux-cored wires for steel with a tensile strength of 610 MPa class. The microstructure and carbide morphology after PWHT at 620℃ were examined. The results have revealed that the size of cementite particles precipitating along the prior austenite grain boundaries significantly affects the toughness. Presumably, this was caused by the cementite precipitates acting as the initiation sites of grain boundary fracture. To refine the cementite precipitates on grain boundaries, it has been found to be effective to adjust the content of C, as well as that of Cr and/or Mo, carbide forming elements. This study has resulted in a weld metal with an optimal composition for HT610 class steel, the weld metal having an excellent strength after PWHT and toughness at -40℃.

Introduction

In the construction of spherical tanks and pressure vessels, etc., post weld heat treatment (hereinafter referred to as "PWHT") is performed to reduce the residual stress introduced by welding, thereby to improve the toughness and fatigue characteristics. With the recent increase in energy demand, these structures are becoming larger and used under higher pressures. Therefore, the strength of the steel adopted has been increasing. Along with the increasing strength of steel, welding materials are also required to have higher strength. In addition, there is a demand for rutile-type flux-cored wire (hereinafter referred to as "FCW") having excellent weldability in all positions in order to facilitate welding works. Conventional rutile-type FCW, however, have not yet been practically applied to the welding of steel with a tensile strength of 610 MPa class (hereinafter referred to as "HT610") or higher, due to the problem that the toughness of the weld metal greatly decreases after PWHT.[1), 2)]

The embrittlement after PWHT in the weld metal of steel having a tensile strength of 550 MPa class or below has been considered to be partially attributable to the fact that the impurity elements, Nb and V, form carbides and cause precipitation hardening.[3), 4)] In the case of the weld metal for steel of HT610 class or higher, however, a mere reduction of these impurities cannot sufficiently improve the toughness after PWHT, and further toughness improvement by microstructure control has been required.

In the present research, weld metals have been prepared using rutile-type FCW for HT610 class steel to examine the relationship between the toughness and microstructure after PWHT. In addition, the effect that each alloying element has on the microstructure has been examined with the aim of finding the composition of weld metal exhibiting favorable toughness even after PWHT.

1. Experimental method

Prototype FCW, each containing various elements, were made for low-alloy, high-tensile strength steel (HT610 class). **Table 1** shows the composition ranges of the weld metal prototypes in the present research. Pairs of test plates, each 20 mm thick, were arranged with a groove angle of 20° and a root opening of 16 mm to be subjected to multilayer welding under a shielding gas consisting of 80% Ar+20% CO_2 to form weld metals. The test plates were made of JIS G 3106SM490A, and a double layer of buttering was formed on each groove surface with the prototype wire so as to prevent dilution by the base material. The average heat input during welding was 1.2 kJ/mm, the preheating temperature was 90 to 110℃, and the inter-pass temperature was 140 to 160℃. After welding, PWHT was performed at 620℃ for 8 hours. Each specimen for the tensile test and Charpy impact test was cut out from the center portion of the respective weld metal to evaluate its strength and toughness. The microstructure of each weld metal was observed by an optical microscope and transmission electron microscope (TEM). The samples for TEM observation were prepared by the extraction replica

Table 1 Chemical composition range of deposited metal used for this study (mass%)

C	Si	Mn	Ni	Cr	Mo	Ti	B	Fe
0.03 - 0.06	0.1 - 0.3	1.3 - 2.0	0.9 - 3.0	0.02 - 0.76	0.2 - 0.6	0.05-0.07	≦0.004	Bal.

method.

2. Decrease in toughness due to PWHT

A weld metal (HT690 class; chemical composition, 0.05%C-0.36%Si-1.90%Mn-0.89%Ni-0.42%Mo-0.07%Ti-0.003%B) has been made using a conventional consumable of Kobe Steel. Its mechanical properties in the as-welded state and after PWHT are shown in **Fig. 1**. The tensile strength satisfies the criteria of 610 MPa or higher even after the PWHT. The Charpy absorbed energy at -40℃, however, declines greatly to 37J after the PWHT from 90J of the as-welded state. **Fig. 2**. is the scanning electron micrograph (SEM) of the fracture surface of the specimen subjected to the Charpy impact test (-40℃) after the PWHT. The fracture surface exhibits a number of cracks along the prior austenite grain boundaries, indicating the occurrence of grain boundary fracture, which is considered to have decreased the absorbed energy.

Fig. 3 shows the optical micrographs (OM) and TEM micrographs of the weld metal. The optical micrographs show no significant difference between the as-welded and PWHT states. The TEM micrographs, on the other hand, show that the carbides, both on the grain boundaries and in the grains, have been coarsened by the PWHT. In particular, coarse carbides are precipitated in a continuous manner along the prior austenite grain boundaries, suggesting that they may have acted as the initiation sites of grain boundary fracture and have decreased the toughness.

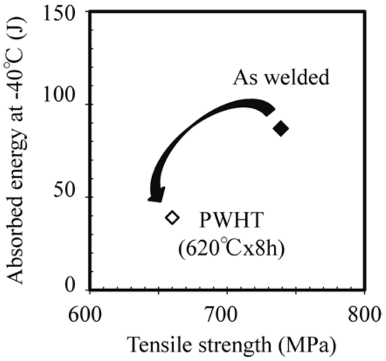


Fig. 1 Mechanical properties of weld metal with conventional wire (HT690 class)

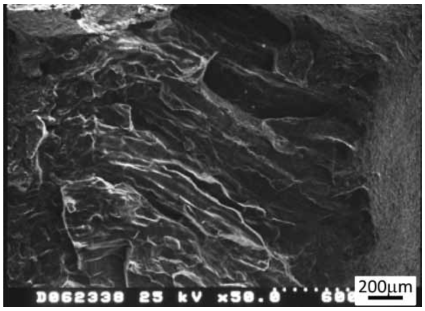
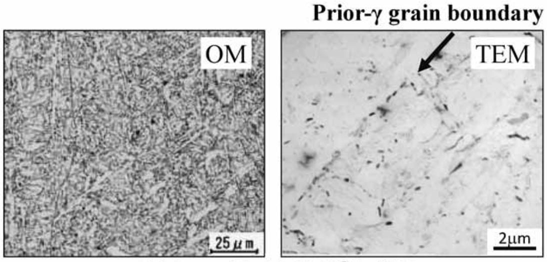
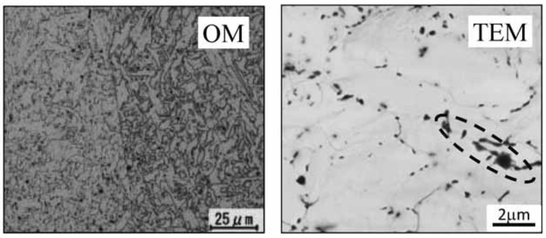


Fig. 2 Fracture surface of Charpy impact test specimen at −40℃ after PWHT



(a) As welded (vE-40℃=87J)



(b) PWHT (vE-40℃=36J)

Fig. 3 Microstructures of weld metal

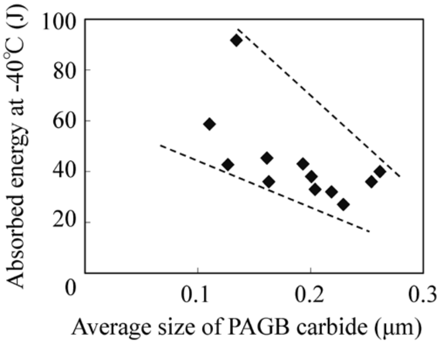


Fig. 4 Relationship between carbides sizes at prior-austenite grain boundary (PAGB) and absorbed energy at −40℃

Fig. 4 shows the relationship between the size of carbides along the prior austenite grain boundaries and the absorbed energy at -40℃ for the composition in the range shown in Table 1. The size of carbide particles has been determined as the average value of the equivalent circle diameter corresponding to the area of carbides precipitating along the prior austenite grain boundaries observed in the bright field image of the TEM. As the size of the carbides on the grain boundary increases, the absorbed energy decreases, showing a clear correlation between the size and absorbed energy. It is thought that preventing the coarsening of the carbides on grain boundaries during PWHT is effective in preventing toughness from declining. Hence, we have focused on C and the major carbide forming elements, Mo and Cr, to examine the effect of these elements on the formation of carbide and on toughness.

3. Effect of C, Mo and Cr on carbide formation and toughness after PWHT

3.1 Effect of C

The effect of C was studied. **Fig. 5** shows the relationship between the content of C in weld metal and the size of carbides along the prior austenite grain boundaries after the PWHT. The figure shows that the size of carbides tends to increase as the C content increases. An increase in C content simply contributes to an increase in the size of carbide and, hence, the toughness after PWHT is considered to be improved by reducing the content of C. The reduction of C content, however, simultaneously reduces the hardenability of the weld metal, which causes the coarsening of the microstructure. Therefore, its lower limit must also be considered. In the case of the present research, coarse ferrite was formed along the prior austenite grain boundaries when the C content was less than 0.04%, causing a decrease in toughness in the as-welded state. Therefore, a C content of approximately 0.04% is considered necessary.

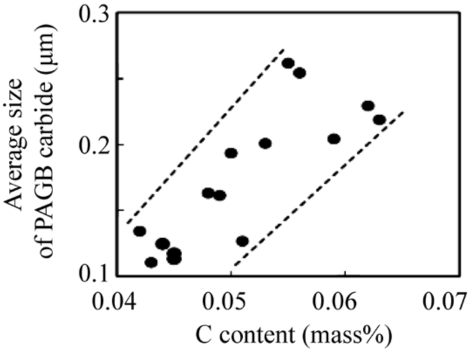
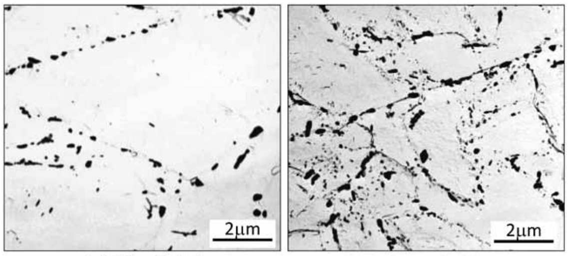


Fig. 5 Relationship between carbon content in weld metal and carbide size at PAGB

3.2 Effect of Mo

Next, the effect of Mo was examined. **Fig. 6** shows the relationships among the content of Mo in the weld metal, the size of carbide on prior austenite grain boundaries after PWHT and the absorbed energy at -40℃. As the Mo content increases, the carbides along the prior austenite grain boundaries become smaller, but the absorbed energy was found to decline. In particular, when the Mo content exceeds 0.4%, there is a significant decline in absorbed energy. **Fig. 7** shows the TEM micrographs after the PWHT of the weld metals containing 0.2% and 0.6% of Mo. As the Mo content increases, fine intragranular precipitates are observed to increase. These precipitates are Mo_2C, and the intragranular formation of Mo_2C is considered to suppress the growth of carbides on grain boundaries to some extent. The intragranular precipitation of Mo_2C, however, causes secondary hardening. In other words, the embrittlement due to hardening might have been more pronounced, resulting in the reduction of toughness. In order to secure the



(a) Mo =0.2% (b) Mo=0.6%

Fig. 7 TEM micrographs of weld metal containing 0.2% Mo and 0.6% Mo

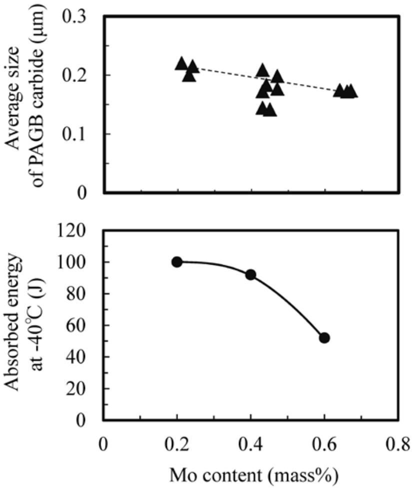
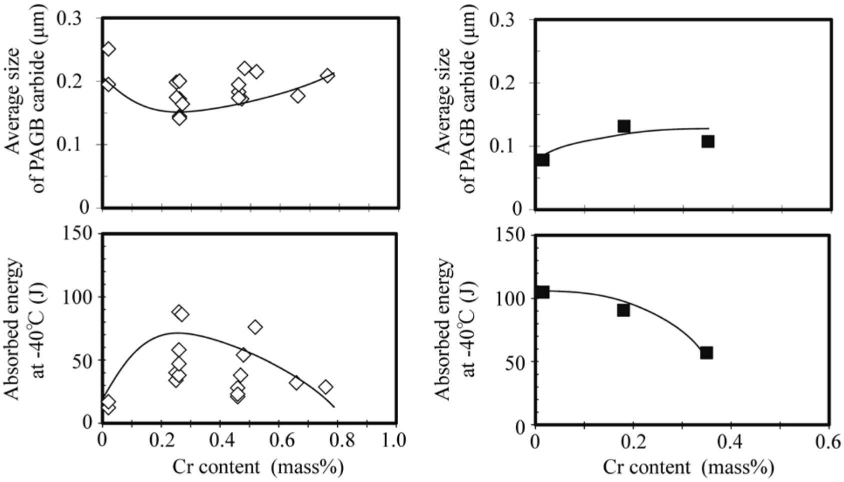
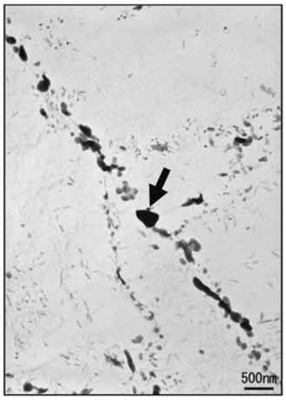


Fig. 6 Relationships among Mo content in weld metal and carbide size at PAGB and absorbed energy at −40℃

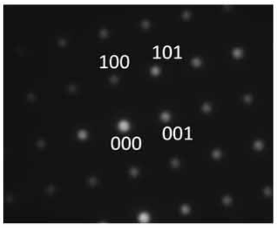


(a) Ni =0.9% (b) Ni=2.5%

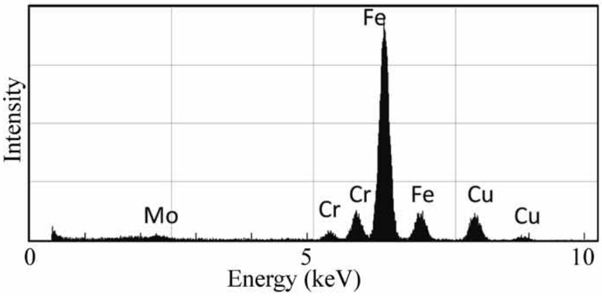
Fig. 8 Relationships among Cr content in weld metal and carbide size at PAGB and absorbed energy at −40℃



(a) Bright field image

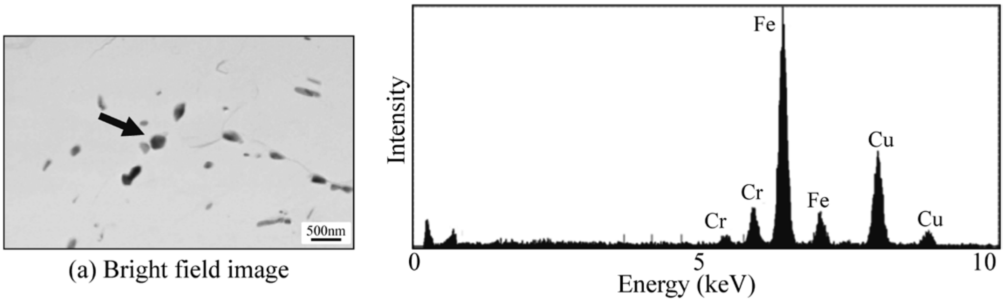


(b) SAD pattern



(c) EDX spectrum

Fig. 9 TEM micrograph of weld metal (0.9%Ni, 0.26%Cr)



(a) Bright field image

(b) EDX spectrum

Fig.10 TEM micrograph of weld metal (2.5%Ni, 0.18%Cr)

strength of HT610 class steel while suppressing embrittlement, the amount of added Mo should preferably be set to approximately 0.4%.

3.3 Effect of Cr

Finally, the effect of Cr was studied; the results are as follows. In the case of Cr, different behaviors of carbide precipitation have been observed, depending on the amount of Ni added simultaneously. **Fig. 8** shows the relationship of the Cr content in the weld metal, the size of carbide along the prior austenite grain boundaries after PWHT, and the absorbed energy at-40℃ for two levels of Ni addition (0.9%, 2.5%). Although the data scatter, the weld metal with Ni content of 0.9% exhibits the minimum carbide size and maximum absorbed energy at a Cr content of approximately 0.25%. On the other hand, in the case of the weld metal containing 2.5% of Ni, the smaller the amount of Cr contained, the smaller the size of carbide becomes, resulting in an increased amount of energy being absorbed.

Fig. 9 shows the TEM micrograph of grain boundary carbides formed in the weld metal containing 0.9% of Ni and 0.26% of Cr. This figure includes the selected area diffraction (SAD) pattern, Fig. 9 (b), and energy dispersive X-ray spectrum (EDX), Fig. 9 (c), both obtained from the coarse carbide shown by the arrow in the bright-field image of Fig. 9 (a). The analysis of the SAD pattern has identified the carbide as cementite, whereas the EDX analysis has confirmed that Cr has dissolved into the cementite, forming a solid solution. It is known that Cr dissolves into cementite to form a solid solution and suppresses the growth of cementite.[5), 6)] It is considered that the growth of cementite has been suppressed by Cr, which has a low diffusion rate, and, as a result, the size of the cementite has been minimized at a Cr content of approximately 0.25%. Meanwhile, the Cr content exceeding 0.25% is considered to have increased the supply of Cr necessary for the growth of cementite, resulting in the loss of the above suppressing effect and, in turn, increasing the size of cementite.

Fig.10 shows the TEM micrograph of the grain boundary carbides formed in the weld metal containing 2.5% Ni and 0.18% Cr. The grain boundary carbides in the bright-field image in Fig.10 (a) were formed in an amount smaller than that of the ones in Fig. 9 (a) and are slightly smaller in size. Fig.10 (b) shows the EDX analysis result for the carbide indicated by the arrow in Fig.10 (a). From the fact that Cr is detected as in the case of Fig. 9 (c), this carbide is considered to be cementite with Cr dissolved in the solid solution. In the case of a 2.5% Ni system as well, the dissolved Cr is considered to have the effect of suppressing cementite growth; however, as shown in Fig. 8, the size of the carbides after PWHT increases as the Cr content increases in the 2.5% Ni system. This led to our study on how Cr content affects the amount of cementite formed.

The amount of cementite formed at 620℃ in the compositions respectively containing 0.9% and 2.5% of Ni was calculated against the Cr content (**Fig.11**). The calculation was performed using the thermodynamics calculation software, Thermo-Calc (Thermo-Calc Software AB, Ver. S, database: TCFE7). When the Ni content is 0.9%, the amount of cementite formed hardly changes with the Cr content; however, when the Ni content is 2.5%, the amount of cementite formed decreases greatly along with the decrease in Cr content. These results indicate that, in the compositions containing 2.5% Ni, the suppression effect on the formation of cementite, an effect due to reduced Cr, had a greater influence on the growth of cementite than did the suppression caused by the addition of Cr, which resulted in the refining of cementite.

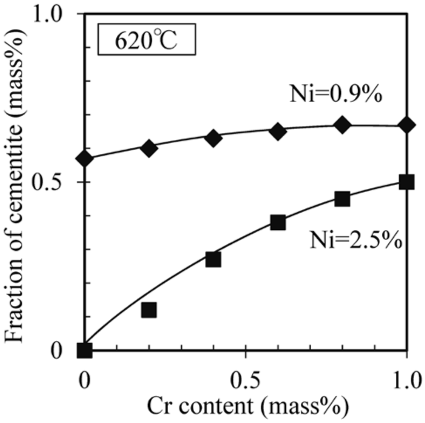


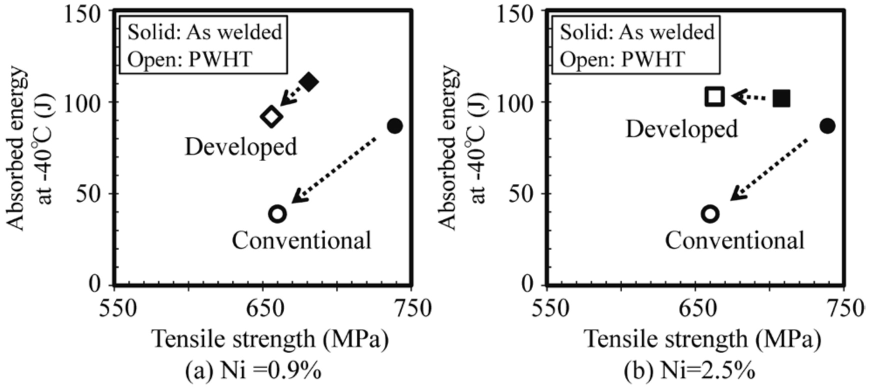
Fig.11 Fraction of cementite at 620℃ calculated by Thermo-Calc

4. Mechanical properties of weld metal with optimal composition

From the above, two weld metal systems, containing 0.9% and 2.5% of Ni respectively, have been optimized as shown in **Table 2**. The mechanical properties of these systems are shown in **Fig.12**. It has been known that Si and Mn promote the grain boundary segregation of P.[7, 8] On the basis of this knowledge, and from the consideration of the balance between strength and toughness, the additive amount of Si has been set to 0.15%, and that of Mn to 1.4%. Both of the weld metals of the above composition systems exhibit tensile strengths higher than 610 MPa, a sufficient strength for HT610 class steel, after PWHT at 620℃ for 8 hours. Furthermore, the absorbed energy at -40℃ after PWHT is greater than that of the conventional material. In particular, the 2.5% Ni-type shows no decline in the value even after PWHT. It should be noted that the weld metals of both compositions exhibit no grain boundary

Table 2 Optimal chemical compositions of weld metal obtained in this study (mass%)

	C	Si	Mn	Ni	Cr	Mo	Ti	B
WM1	0.04	0.16	1.37	0.96	0.42	0.39	0.05	0.002
WM2	0.05	0.15	1.45	2.50	0.02	0.30	0.05	0.002



(a) Ni =0.9%
(b) Ni=2.5%

Fig.12 Mechanical properties of weld metal obtained in this study fracture on the fracture surfaces of the Charpy impact test pieces after PWHT. The 2.5% Ni-type FCW, showing excellent toughness after PWHT, has been commercialized as "TRUSTARC™[note 1] DW-A62LSR."

Conclusions

Regarding the weld metal made from FCW for high-tensile strength steel (HT610 class steel), a study was conducted to examine the relationships after PWHT among the microstructure, carbide formation and toughness to pursue the weld metal composition for realizing favorable toughness. The results obtained in the present research are as follows:

(1) The relationship between the size of carbide on the prior austenite grain boundaries and toughness after PWHT has been examined and, as a result, a clear correlation has been found between them. The decrease in toughness after PWHT is considered to be attributable to the coarsened carbide (cementite) acting as initiation sites of grain boundary fracture.

(2) The effects of C and of the major carbide forming elements Mo and Cr on carbide formation and toughness were examined. It was found to be desirable to hold the addition of C down to 0.04% and Mo to about 0.4%. It was revealed that the effect of Cr differed depending on the amount of Ni added.

(3) The study yielded two weld metal systems, respectively containing 0.9% and 2.5% of Ni, and their mechanical properties after PWHT have been evaluated. Each system exhibits a tensile strength sufficient for HT610 class steel and a toughness more favorable than that of conventional material.

(4) The 2.5% Ni-type FCW, showing the most excellent toughness after PWHT, has been commercialized as "TRUSTARC™ DW-A62LSR."

References

1) K. Suenaga et al. *R&D Kobe Steel Engineering Reports*. 2004. Vol.54, No.2, pp.38-42.
2) C. Y. Kang and S. H. Jeong. *Journal of Welding and Joining*. 2014. Vol.32, No.4, pp.75-79.
3) K. Hosoi et al. *Quarterly Journal of the Japan Welding Society*. 2016. Vol.34, No.2, pp.81-92.
4) T. Suga et al. *IIW Doc. XII*-1492-97. 1997. pp.3-25.
5) T. Sakuma. *Bulletin of the Japan Institute of Metals*. 1981, Vol.20, No.4, pp.247-256.
6) S. Shimoyama et al. *R&D Kobe Steel Engineering Reports*. 2008. Vol.58, No.1, pp.36-38.
7) J. Kameda. *Bulletin of the Japan Institute of Metals*. 1980. Vol.19, No.8, pp.595-603.
8) K. Yamanaka. *TETSU-TO-HAGANE*. 1980. Vol.66, No.9, pp.91-98.

[note 1] TRUSTARC™ (TRUSTARC™) is a registered trademark of Kobe Steel.