Distribution and reduction in P concentration of submerged arc welding slag
— Trials for reusing welding slag as welding flux —

by KOJIMA Kazuhiro**, SUZUKI Masanori*** and TANAKA Toshihiro***

Submerged arc welding (SAW) is widely used in the fields such as ship buildings and steel pipe production. Recently reuse of SAW slag as a raw material of SAW flux has been discussed, as a measure to reduce costs and to conserve natural resources. The present study investigated distribution of P in the slag and its major origin (i.e., welding wire or base metal plate). It also proposed slag remelting as a method of P concentration reduction of the slag. It was recognized that P was mainly distributed in the matrix and metallic steel particles with only larger diameters. It was also identified that the base metal plate was the main source of P in the slag. Remelting of the slag was proved as a promising method for P concentration reduction of the slag.

Key Words: Submerged arc welding, Low alloy steel, Slag, Reuse, Flux, Metallic steel particles, P concentration reduction, Slag remelting

1. Introduction

Welding is indispensable in the fabrication of modern steel structures; arc welding is particularly often used for its advantages in economy and efficiency. Among the various arc welding techniques, highly efficient submerged arc welding (SAW) is widely used in many industries such as ship buildings and steel pipes production, where multiple electrodes can be applied which can allow high heat input and process automation. In SAW process, the flux melts into slag to protect the molten pool, helping the formation of sound welded joints. In recent years, the reuse of slag into SAW flux has been discussed, as this effectively reduces the material costs and facilitates the sustainable use of global resources, such as TiO$_2$ and Al$_2$O$_3$.

In the earlier paper, it was found that the original flux and by-produced slag had an almost identical chemical compositions except Fe and P contents which were higher in the slag than in the original flux. Furthermore, based on the results of X-ray diffraction analysis, it was determined that the flux and slag had the same crystal structure. It was also found that Fe existed partly in the form of metallic steel particles (hereinafter “M. S. particles”) in which Fe was the main component in the slag. It could be assumed that M. S. particles were formed by the evaporated Fe and other alloy elements. It was also discussed that the main source of M. S. particles was not the base metal plates but the welding wires.

The safe reuse of slag as a raw material of SAW flux requires a precise understanding of P distribution in the slag, as P was reported to increase during the transformation process from the flux to slag. The present study then investigated distribution of P in the slag and its major origin (i.e., welding wire or base metal plate). It also proposed a slag remelting process as P concentration reduction method of the slag. Slag remelting was attempted by which P was collected into M. S. particles in order to reduce P concentration of the matrix. This process was demonstrated by simulating experiments with fairly long term situation which can allow P transfer from the matrix into M. S. particles. Note that in the present study, “flux” and “slag” refer to the powder that is laid on the base metal plates and solids formed on the weld metal surface out of the molten flux respectively.

2. Experimental procedures

Slag samples A and C were the same as those reported in the previous paper. They were both formed from the identical welding flux (i.e., Flux A in the earlier paper), but Slag A and Slag C were obtained with 0.021 mass% P base metal and, in contrast, 0.019 mass% P welding wire respectively. These base metal and wire were selected in order to identify the major origin of P in the slag.

It was verified that Al, Si, Ti, Mg, Mn, Ca, F, K, C and S contents remain unchanged in the transformation of flux into slag. Furthermore, the change in Fe content was addressed in the previous paper. The present study, therefore, focused on the distribution and reduction in P concentration of the slag.

Slag A and C were pulverized into powder for use as specimens after removing residual flux from the slag as described in the earlier paper. The P content was analyzed by "wet method", which is described below in detail. The solution was first prepared by

---

1. The Matrix refers the major part of the slag, which contains P, excepting M. S. particles
mixing the slag powder with a mixture solvent of HCl and HNO₃. The residue of the above procedure was melted with Na₂CO₃ in a Pt crucible by gas burner heating. After melting, solidifying and cooling, it was mixed with a HCl solvent to form another solution. These two solutions were mixed as the specimen for high frequency inductively coupled plasma (ICP) emission spectroscopy to determine the total P content in the slag ("T. P" content). In addition, Exclusive extraction of M. S. particles was attempted using the bromine methanol solution in order to quantify the P content in M. S. particles. After removing bromine methanol solvent by evaporation, the residual salt was dissolved in a HCl solution. ICP emission spectroscopy was then performed on the solution to quantify the P content of M. S. particles included in the slag ("M. P" content).

The analysis conducted using the wet method can determine the average P content in the slag, but it does not give any information on the distribution of P or on the P content in individual M. S. particles. Electron probe microanalysis (EPMA) was then employed to determine the content and distribution of P in M. S. particles having the most frequently appeared diameter, approximately 1 μm, identified in the earlier paper⁶. A field emission (FE) type EPMA, “JEOL Model JXA8500F” of JEOL Ltd. was used in the present study. EPMA specimens were prepared by cut, mirror-polish and carbon vapor deposition to ensure electric conductivity on the bulk slag specimens. Analysis conditions were as followings (except for the analysis for obtaining P content calibration line, which will be described later). Magnification factor, irradiation current and acceleration voltage were 5000, 0.05 μA and 15 kV respectively. Area of analysis was 50 x 50 μm and was divided into 62500 (250 x 250) cells for simultaneous analysis of Fe and P contents. Analysis time was 50 ms per cell.

For quantitative analysis by EPMA, it is necessary to determine the calibration line in advance using a material of known composition. Since no certified reference material (CRM) for P content analysis with EPMA was commercially available, “11X HPC1 (batch H)” and “11X HPC3 (batch J)” were used which were the CRMs for optical emission spectroscopic and fluorescent X-ray analysis. They were supplied by MBH Analytical Ltd in a cylindrical shape with 40 mm diameter and 17 mm thick. Table 1 shows the chemical compositions of these CRMs. The CRMs were prepared by, mirror-polish and carbon vapor deposition on their circular cross-sections. Analysis conditions were as followings. Magnification factor, irradiation current and acceleration voltage were 2500, 0.5 μA and 15 kV respectively. Area of analysis was 20 x 20 mm and was divided into 250000 (500 x 500) cells for analysis of P content. Analysis time was 50 ms per cell. The signal strength for 0 mass% P content was referenced to the background base signal level in a wavelength range outside the P spectrum.

Chemical compositions of SAW slag for remelting investigation are shown in Table 2. They were almost the same as those of Slag A⁸. T. P content was determined by the same method as described above. The other ones were done by the same method as described in the earlier paper⁵. 30 kg SAW slag was put into a graphite crucible having a size of 300 mm and 270 mm in outer diameter and height respectively. The slag was remelted in the furnace (“Model ALF-00” made by ANDO INDUSTRIAL CO., LTD) equipped with three graphite electrodes. C contents of the crucible and electrodes were 99.9 and 99.7 mass% respectively. These

**Table 1** Chemical compositions of certificated reference materials for EPMA

| Make                        | Brand name   | C  | Si  | Mn  | P       | S       | Ni | Cr | Mo | Balance       |
|-----------------------------|--------------|----|-----|-----|---------|---------|----|----|----|---------------|
| MBH ANALYTICAL LTD          | 11X HPC1 (batch H) | 3.29 | 3.27 | 0.820 | 0.808 | 0.0035 | 1.056 | 0.060 |
|                             | 11X HPC3 (batch J) | 3.38 | 1.63 | 1.287 | 2.01 | 0.0473 | 2.18 | 1.48 | 0.120 |

Blank cell: No data is reported

**Table 2** Chemical compositions of SAW slag for remelting investigation (mass%)  

| Si  | Al  | Mn  | Mg  | Ca  | Ti  | F   | #1 T. Fe | #2 M. Fe | #3 T. P | K   | C   | S   | Balance   |
|-----|-----|-----|-----|-----|-----|-----|----------|----------|----------|-----|-----|-----|-----------|
| 19.9 | 2.0 | 32.5 | 1.1 | 3.6 | 0.1 | 1.9 | 4.25      | 0.91      | 0.01     | 1.2 | 0.03 | 0.041 | O and impurities |

*1) T. Fe; Total Fe  
*2) M. Fe; Metallic Fe  
*3) T. P; Total P
graphite crucible and electrodes were selected because of their less reaction with molten slag and reduction agent function that makes P transfer easier from the matrix to M. S. particles. Temperatures of the molten slag during remelting were controlled to approximately 1823 K. After remelting, the slag was cooled to the room temperature in the powered-off furnace. The remelted slag with the crucible was inspected by 3-D X-ray radiography to determine the location of steel precipitates. The 3-D X-ray inspection was performed with “TOSCANER 24500 twin” of Toshiba and 3-D software, “VG Studio MAX 2.2” of Volume Graphics.

The sample for chemical composition analysis of the remelted slag was extracted from the center of the bulk sample. The 100 mm height portion from the outer bottom was taken out to analyze chemical compositions of the steel precipitates. The slag with crucible of this portion was milled to obtain steel grains by magnetic separation. Chemical compositions of such steel grains were analyzed in order to discuss the reduction mechanism in P concentration of the slag, as simulating experiments with fairly long term situation which can allow P transfer from the matrix into M. S. particles. The steel sample for chemical composition analysis was prepared through surface grinding to avoid contamination of the slag. It was then pulverized with a WC crusher for wet analysis.

3. Results

Table 3 shows the results of P content of Slag A and C by wet method. It also shows P content of the welding wire, base metal plate and weld metal for obtaining slag A and C. In the case of slag A, by the welding wire and base metal with the P content of 0.005 and 0.021 mass% respectively, the T. P content was obtained. In the case of slag C, however, by the welding wire and base metal with the P content of 0.019 and 0.005 mass% respectively, the T. P content was not quantifiable, because it was below the analysis threshold. With both of slag A and C, M. P contents were not quantifiable because they were also below the analysis threshold. P contents were simply compared between Slag A and C in the present study, which did not intend to quantify the existence of P below the analysis threshold (i.e., 0.005 mass%).

Fig. 1 shows P content mappings of the CRMs by EPMA as well as the calibration line determined on these mapping results.

| ID  | Slag T P | M. P | Welding wire | Base metal plate |
|-----|----------|------|--------------|-----------------|
| Slag A | 0.010 | <0.005 | 0.016 | 0.005 | 0.021 |
| Slag C | <0.005 | <0.005 | 0.013 | 0.019 | 0.005 |

![Fig. 1 P content mappings by EPMA on CRMs and their calibration line](image-url)
linear relationship was obtained between the P contents and the characteristic X-ray strengths. Based on these results, the P content calibration line was assessed to be valid when it was obtained by averaging signal strengths from sufficiently large areas of the CRMs, even though the CRMs were not originally intended for quantitative use in EPMA.

Fig. 2 shows combined mappings of Fe and P-detected locations by EPMA. It was recognized that P was mainly distributed in the matrix and M. S. particles with only larger diameters. Fig. 3 shows the results of the quantitative mapping of P content by EPMA in the same analysis area as in Fig. 2. It seems that the distributions of P and Fe are not always identical; this inconsistency will be examined in more detail in the next section of discussions.

An example of the situations of remelting experiment is shown in Fig. 4. Fig. 5 shows the results of 3-D X ray inspections of the slag in crucible. Fig. 5 (a) shows the 3-D indication of steel portion exclusively extracted by image processing. Fig. 5 (b) shows the cross-section radiographs along the height direction. Steel precipitates (see chemical compositions shown in Table 4) were recognized. They were mainly located on the inner bottom and on the side wall of the graphite crucible. The weight of steel precipitates obtained by magnetic separation was 746 g. Chemical compositions of the steel grain shown in Fig. 6 are listed in Table 4. P was enriched in it to 0.27 mass%. Chemical compositions of the remelted slag are shown in Table 5. It can be found that T. P, T. Fe and M. Fe contents were decreased by remelting, according to the comparison of the compositions between before and after remelting.
Table 4  Chemical compositions of steel grain shown in Fig. 6 (mass%)

| C   | Si  | Mn  | P   | S   | W  | #1 Fe | #2 Fe |
|-----|-----|-----|-----|-----|----|-------|-------|
| 3.78| 4.52| 26.0| 0.27| <0.002| 0.04| 62.9  | 61.6  |

*1) T. Fe, Total Fe
*2) M. Fe, Metallic Fe

Fig. 5  Results of 3-D X ray inspection of slag and graphite crucible
(Numbers of (b) in each cell show distance from outer bottom of crucible)

Table 5  Comparison of chemical compositions of slag between before and after remelting (mass%)

| Status         | Si  | Al  | Mn  | Mg  | Ca  | Ti  | F   | #1 T. Fe | #2 M. Fe | #3 T. P | K   | C  | S  | Balance       |
|----------------|-----|-----|-----|-----|-----|-----|-----|----------|----------|---------|------|----|----|----------------|
| Before remelting| 19.9| 2.0 | 32.5| 1.1 | 3.6 | 0.1 | 1.9 | 4.25     | 0.91     | 0.01    | 1.2  | 0.03 | 0.041 | O and impurities |
| After remelting | 20.5| 2.0 | 33.6| 1.1 | 3.6 | 0.1 | 1.9 | 1.90     | 0.49     | <0.005  | 1.1  | 0.04 | 0.032 | O and impurities |

*1) T. Fe, Total Fe
*2) M. Fe, Metallic Fe
*3) T. P, Total P

Fig. 6  Appearance of a steel grain obtained from remelted slag for chemical composition analysis
4. Discussions

According to the results in Table 3 showing the P content in slag obtained by the wet method, it could be assumed that the P in slag originated mainly from the base metal. Komen et al. assumed 25000 K as the arc temperature in the vicinity of the tip of the welding electrode and a much lower temperature such as around 2500 K for the molten pool under the welding electrode for numerical calculations on the SAW phenomena\(^9\). The boiling point of P differs among its allotropes. However, even in the case of red P which has a relatively high boiling point, it is as low as 703 K. Therefore, unlike Fe and Ni discussed in the previous paper\(^9\), P would not be required such a high temperature as calculated in the vicinity of the welding electrode tip in the arc for its evaporation from the molten pool. The arc dimension determined by Komen et al. resembles the shape of a bell as the arc spreads itself from the tip of the electrode to the molten pool. Considering that the molten pool apparently has a larger surface area, than one of the electrode tip, which permits the evaporation of P efficiently, the welding wire was not considered as the major source of the P in slag among the materials related to the welds.

When it is assumed that the P in slag originates from the molten pool, this assumption raises the further argument why P was quantifiable only in the analysis of slag A using the wet method. Table 3 shows that the P content in the weld metal was 0.016 mass% in the welding that produced slag A, while it was 0.013 mass% in the welding that produced slag C. Since the difference between the above two figures is as small as 0.003 mass%, it is difficult to attribute the difference in the P content in the weld metal to the difference in the P content in the molten steel. Although it is difficult to explain the reason of this P content difference in the slag at this point, Fig. 7 may work for a qualitative explanation.

Komen et al., in the numerical calculations, defined the “arc space” (equivalent to the “arc cavity” in Fig. 7) as the space where the temperature is equal to or higher than 25000 K which is the boiling point of SiO\(_2\). It was stated that the calculations were consistent with the X-ray radiographic observation of the SAW phenomena\(^10\). According to the view of Komen et al., the temperature in the arc cavity is about 700 K higher than the melting point of Fe (1809 K) but lower than its boiling point (3160 K). It was assumed, therefore, that a part of the frontal portion of the molten steel contacted with the arc cavity and the other posterior part did with the molten slag. When the molten steel is in contact with the molten slag, the latter functions as plug and prevents the evaporation of P from the molten steel. In both of the welding that produced slag A and C, the nitrogen contents in the weld metal were sufficiently low at 40 ppm\(^9\). It was, therefore, deduced that the molten steel was in close contact with the molten slag without a gap, causing the molten steel to be tightly sealed by the molten slag.

In contradistinction to in the molten pool, in the arc cavity, there is no molten slag to work as plug. It seems, therefore, plausible that the evaporation of P can easily take place in the arc cavity. According to the above assumptions, the evaporation of P is expected to take place from the frontal part of the base metal that is in contact with the arc cavity and also from the frontal part of the molten steel. The P that evaporated from the base metal thus was likely to have made the greatest contribution to the T. P content. It could be concluded that these supposition might explain the reason for that T. P content was obtained only in slag A from welding with the 0.021 mass% P base metal and it was not quantifiable in slag C with the 0.005 mass% P base metal.

The reason for that M. P contents were not quantifiable in both of the slag samples is then discussed. Turkdogan and Pearson propose equations (1) through (6) describing the transfer of P from molten steel to slag\(^11\).

\[
\begin{align*}
5O + 2P &= P_2O_5 \text{ (liquid)} \quad (1) \\
K_P &= \frac{a_{P_2O_5}}{[O_2]^5[P]^2} \quad (2) \\
K_P; & \text{ Equilibrium constant, } a_{P_2O_5}; \text{ Activity of P}_2O_5 \\
\log K_P &= \frac{36850}{T} - 29.07 \quad (3) \\
T; & \text{ Absolute temperature} \\
\log y_{P_2O_5} &= -1.12 \sum A_i N_i - \frac{42000}{T} + 23.58 \quad (4) \\
Y_{P_2O_5} &= \frac{a_{P_2O_5}}{N_{P_2O_5}} \quad (5) \\
\sum A_i N_i &= 22N_{CaO} + 15N_{MgO} + 13N_{MnO} + 12N_{FeO} - 2N_{SiO_2} \quad (6)
\end{align*}
\]

\(N_i;\) Mole fraction of oxide \(i\)  
\(A_i;\) Coefficient of oxide \(i\)

![Fig. 7 Schematic diagram of SAW phenomena](image)
Equilibrium constant $K_P$ in Equation (1) is defined by Equation (2) and its temperature dependency is defined by Equation (3). These equations show that the transfer of $P$ from the molten steel to slag proceeds more efficiently at lower temperatures. The activity coefficient of $P_2O_5$ in slag ($\gamma_{P_2O_5}$) is given by Equations (4) through (6). According to these equations, the transfer of $P$ from the molten steel to slag will be assisted by minimizing the calculation result given by Equation (4) and maximizing one given by Equation (6).

Because of the chemical compositions of the slag, once exposed to high temperature in arc, $P$ was expected to exist primarily in M. S. particles. However, the experiment results shown in Table 3 and Fig. 2 did not support this assumption. It could be rather assumed that M. S. particles with smaller diameters were likely to solidify before $P$ transferred into them from the surrounding matrix. This assumption can work for a qualitative explanation for the above apparent discrepancy. In the earlier paper relationship between M. S. particle diameter in the two dimensional observation and their number density (number per unit area) was reported. It showed the extreme scarcity of M. S. particles having a diameter of 2 $\mu m$ or larger, that might rationalize the results shown in Table 3.

For quantitative discussions on the EPMA, $P$ content in M. S. particles, it is necessary to focus on the M. S. particle size. While a field emission (FE) type EPMA was adapted, the generation of characteristic X-rays can take place from a region of 1 $\mu m^3$ or larger. With M. S. particles of less than 1 $\mu m^3$, the presence of matrix around them may cause interference. Therefore, as in the previous study, from the results in Fig. 3, only those portions where the Fe content was 10 mass% or greater were extracted, ignoring the presence of Fe oxides to plot the relationship between the M. Fe and the $P$ content in Fig. 8. Incidentally, note that since the $P$ content calibration line was validated up to 2.01 mass%, $P$ content reached 1.2 mass% in Fig. 8 can be rationalized. While a clear correlation between the Fe and Ni contents was observed in the previous study, Fig. 8 did not demonstrate any correlation between the Fe and $P$ contents. This can be attributed to the mismatch between Fe and $P$-detected locations as shown in Fig. 2.

$P$ is one of the detrimental elements for weldability such as hot cracking susceptibility, PWHT embrittlement and reheat cracking. $P$ may transfer from molten slag to molten steel as schematically described in Fig. 9. Therefore, $P$ content of slag should be depressed. In the earlier paper, remelting was proposed as a method to separate Fe from the slag. Based on the following considerations, remelting could also be an excellent method for the reduction in $P$ concentration. When the enough time is given for $P$ in the matrix to transfer into M. S. particles, it should be possible to collect $P$ into the M. S. particles in the slag as shown in Fig. 10. It was inferred that, in the process of remelting, smaller M. S. particles might merge together to form larger M. S. particles in order to decrease the interfacial energy between M. S. particles and the matrix. This process reduces the total number of M. S. particles. They deposit on the bottom of a crucible because of the difference in density between M. S. particles and the matrix, permitting their easy separation. The remelting concept as described in Fig. 10 was supported by the present remelting experimental results. Based on them, it seems to be reasonable that $P$ was enriched in and around M. S. particles with only larger diameters as shown in Fig. 2.
5. Conclusions

The present study investigated the distribution of P in the slag obtained from SAW with a variety of P content in the welding wire and the base metal. The following conclusions were obtained.

1. It was recognized that P was mainly distributed in the matrix and metallic steel particles with only larger diameters.
2. It was assumed that the P in slag originated mainly from the base metal.
3. Slag remelting was proved to be a promising method for the reduction in P concentration of the slag and thus this method should be beneficial for the weldability.

Acknowledgments

The authors gratefully acknowledge Dr. HARA Kyosuke, a researcher of Nippon Steel & Sumitomo Metal Corporation, for his kind assistance of 3-D X ray inspection. The authors are also very grateful to Dr. ICHIKAWA Kazutoshi, a senior researcher of Nippon Steel & Sumitomo Metal Corporation (now a Professor at Tohoku University as well), for his helpful discussions and advices. The authors also appreciate Dr. HIRATA Hiroyuki, the head of Welding & Joining Research Laboratory of Nippon Steel & Sumitomo Metal Corporation, for his generous support on the present study.

References

1) Shigeo OYAMA, Tadashi KASUYA, and Kouichi SHINADA: High Speed One-side Submerged Arc Welding Process “NH-HISAW”, NIPPON STEEL TECHNICAL REPORT, 95 (2007), 17-21.
2) K. SHINADA, Y. HORII AND N. YURIOKA: Development of Weld Metal with High Toughness and Low Hardenability, Welding Journal, 71-7 (1992), 253s-262s.
3) Datta Saurav, Bandopadhyay Asish, and Pal Pradip Kumar: Reclaiming of Submerged Arc welding Slag: Comparison between SAW Processes with and without slag-mix, Indian Welding Journal, 41-3 (2008), 22-31.
4) Saurav Datta, Asish Bandopadhyay, and Pradip Kumar Pal: Submerged Arc Welding With a Mixture of Fresh Flux and Fused Slag-Modeling with Quadratic Response Surface Methodology, Indian Welding Journal, 39-4 (2006), 20-31.
5) Kulwant Singh and Pandey Sunil: Recycled slag consumption in submerged arc welding and its effect on microstructure of weld metal, Indian Welding Journal, 42-4 (2009), 46-51.
6) H. P. BECK AND A.R.JACKSON: Recycling SAW Slag Proves Reliable and Repeatable, Welding Journal, 75-6 (1996), 51-54.
7) DEANNA MURLIN: The Use of Crushed Slag as Submerged Arc Welding Flux, Welding Journal, 89-8 (2010), 41-43.
8) KOJIMA Kazuhiro, MIZUKAMI Kazumi, SUZUKI Masanori, and TANAKA Toshihiro: Comparison of chemical compositions and micro-structure between flux and slag on submerged arc welding, Quarterly Journal of The Japan W elding Society, 36-1 (2018), 60-67 (in Japanese)
9) KOJIMA Kazuhiro, MIZUKAMI Kazumi, SUZUKI Masanori, and TANAKA Toshihiro: Formation mechanism of fine steel particles in submerged arc welding slag, Quarterly Journal of The Japan Welding Society, 36-1 (2018), 68-76 (in Japanese).
10) KOMEN Hisaya, MATSUI Sho, KONISHI Kyohsei, SHIGETA Masaya, TANAKA Manabu and KAMO Takahiro: Modeling of Submerged Arc Welding Phenomena and Experimental Study of the Heat Source Characteristics; Quarterly Journal of The Japan Welding Society, 35-2 (2017), 93-101. (in Japanese)
11) E. T. Turkdogan, and J. Pearson: Activities of Constituents of Iron and Steelmaking Slags Part Ill-PHOSPHORUS PENTOXIDE, JOURNAL OF THE IRON AND STEEL INSTITUTE, 175 (1953), 398-401.
12) BAILEY N., JONES S. B.: The solidification cracking of ferritic steel during submerged arc welding, Welding Journal, 57-8 (1978), 217S-218S.
13) Masaki SHIMAMOTO, Dr. Hitoshi ISHIDA, Shaji SASAKURA, Tomonori KAKIZAKI: Technology for Reducing Solidification Cracking Susceptibility of Carbon Steel Weld Metal, R & D KOBE STEEL ENGINEERING REPORTS, 63-1 (2013), 32-36 (in Japanese).
14) Yukihiko HORII, Shigeru OHKITA, Kazuhiro KOJIMA: Study of PWHT Embrittlement in High Strength Low alloy Weld metals (Paper 2), Journal of High Pressure Institute of JAPAN, 34-1 (1996), 3-7 (in Japanese).
15) Hiroshi Mimura: Temper Brittleness in Steel, Tetsu-to-Hagane, 57-14 (1971), 2273-2284 (in Japanese).
16) Toshiro Kikuchi and Iwao Onishi: Metallurgical Study on the Reheat Cracking in the Weld Zone of Steel, Journal of The Japan Welding Society, 48-11 (1979), 960-966 (in Japanese).
17) YOSHIYUKI UESHIMA, SHOZO MIZOGUCHI, TOORU MATSUMIYA, and HIROYUKI KAJIKA: Analysis of Solute Distribution in Dendrites of Carbon Steel with δ/γ Transformation during Solidification, Metallurgical Transaction B, 17-4 (1986), 845-859.