Depth Profiles of Nitrogen and Oxygen absorbed in HAZ of ZrTN802D Alloy Tube by TIG Welding in Various Atmospheres (Report 2)*

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Abstract

As a study relative to the evaluation of corrosion characteristics in high temperature water of welds of ZrTN802D alloy (Zircaloy-2) tubes, continued investigations were made on the depth profiles of nitrogen (N) and oxygen (O) absorbed in HAZ by TIG welding in various atmospheres.

A calculation was attempted to estimate N depth profiles in a portion heated to β phase temperature range in HAZ. Although the calculated depth profiles were somewhat different from those of SIMS analysis values at the portions nearer the surface, the calculated value was seen to decrease rapidly toward the value of N in base metal with increase of depth. It was also found out by additional chemical and SIMS analyses of N after surface etching of the welds that the depth of diffusion of N in HAZ was not deep under this welding condition.

O was absorbed and diffused in the region heated within α phase range in HAZ, and it was also confirmed that the diffusion depth was shallower.

Key words: TIG welding, Zr alloy, Weld heat affected zone, Nitrogen absorption, Oxygen absorption

1. Introduction

With regard to tube-to-end-plug welding of ZrTN802D (Popularly called as Zircaloy-2, abbreviated herein as Zry-2) tubes, the characteristics of welds which were welded by TIG in atmospheres with various nitrogen and oxygen partial pressures (P_{N_2} and P_{O_2}) at total pressures (P_T) of 0.10 and 0.32 MPa have been investigated by same authors¹⁻⁴⁾. Upon these investigations, it was made clear that the nitrogen (N) and oxygen (O) were absorbed not only in weld metal but in HAZ when P_{N_2} and P_{O_2} increased.

As the corrosion characteristic in high temperature water of welds containing HAZ of Zr alloys is affected by N and O contents therein⁵⁾, it is useful to know the depth profiles of N and O as well as their average values in welds, and the corrosion behavior thereat can be estimated from these profiles.

Therefore, the depth profiles of N and O absorbed in HAZ of Zry-2 tube were measured and evaluated by applying Secondary Ion Mass Spectrometry (SIMS) as related to the microstructure changes therein and the results were reported in Report 1⁶⁾. By this previous report it was made clear that N was absorbed at the region heated to β or $\alpha + \beta$ phase temperature range (abbreviated herein as β phase range) in HAZ and diffused deep into inside when P_{N_2} increased. Also O was absorbed more at the region heated within α phase range rather than β or $\alpha + \beta$ phase range in HAZ and did not diffuse deeper even when P_{O_2} increased.

Based on the results above, with special regard to the diffusion of N which has shown clear absorption in HAZ, a calculation was attempted to determine the depth

profile from surface to deeper portion in HAZ of welds by TIG. Also the depth profiles of N and O in HAZ were investigated by an additional examination.

2. Experimental procedure

2.1 Materials used for the examination

The welding test for this study was carried out by Zry-2 tube-to-end-plug welding. The chemical composition of these materials is shown in Table 1, and the shape of test specimen is shown in Fig. 1. Zry-2 tubes were fabricated by the process of three steps cold rolling and α annealing using an $\alpha + \beta$ quenched tube shell (64 mm ϕ O.D. $\times$ 11 mm t).

2.2 Welding equipment used for the examination

The welding equipment with an evacuation-backfill type welding chamber as shown in Report 1 was used for the examinations.

Table 1 Chemical compositions of Zry-2 tube and end plug (mass%).

Material	Sn	Fe	Cr	Ni	O	N	Zr
Tube	1.29	0.18	0.10	0.07	0.116	0.0032	Bal
End plug	1.30	0.19	0.09	0.07	0.105	0.0031	Bal

Fig. 1 Shape and size of tube-to-end-plug weld test specimen.

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2.3 Welding-test gases

In this investigation, He and Ar gases containing a small quantity of impurities ($N_2=1$ vol.ppm, $O_2=4$ vol.ppm) and containing various quantities of N_2 (≤ 160 vol.ppm) and O_2 (≤ 40 vol.ppm) as shown in Table 2 were used as welding-test gases.

2.4 Welding method and welding condition

The tube-to-end-plug welding for this investigation was carried out in the following manner.

A Zry-2 tube and an end plug were set at the welding chamber, and after the chamber and inside of the tube were evacuated to 6.5×10^{-6} MPa and filled with the welding-test gas, the end plug was seated into the tube end. The gas overflowed to outside of chamber and the pressure in weld chamber (abbreviated herein as P_T) was held at 0.10 and 0.32 MPa during welding by means of a pressure regulator. Under above conditions, welding was performed rotating the tube and end plug synchronously.

Table 3 shows the welding condition. In the case of $P_T=0.10$ MPa, mixed gas with 80 vol.% of He and 20 vol.% of Ar was used to have easier arc starting and to maintain enough deep penetration. On the other hand, in the case of $P_T=0.32$ MPa, only He gas was used to meet specification for the seal welding of the nuclear fuel rod. The tube-to-end-plug welding was performed by two passes without filler metal.

2.5 Surface etching

The welds were etched by 10–40 μm of their surface in

Table 2 Contents of O_2 , N_2 and other impurities in welding-test-gases (vol.ppm).

Gas	Group	O_2	N_2	H_2	CH_4	CO	CO_2
He	1	1	4	≤ 0.5	≤ 0.1	≤ 0.1	≤ 0.1
	2	40	4	≤ 0.5	≤ 0.1	≤ 0.1	≤ 0.1
	3	10 ~ 40	40 ~ 160	≤ 0.5	≤ 0.1	≤ 0.1	≤ 0.1
Ar	1	1	4	≤ 1.0	≤ 0.1	—	≤ 0.1
	2	20	80	≤ 1.0	≤ 0.1	—	≤ 0.1

Table 3 Welding condition.

Weld parameter	Ambient pressure (MPa)	
	0.10	0.32
Electrode dia. *1 (mm ϕ)	1.0	1.6
Arc length (mm)	0.5	0.5
Welding current *2 (A)	10~35	10~28
Welding speed (mm/min)	350	350
Shield gas flow rate (l/min)	He : 20 Ar : 5	He : 25

*1 : 2% Th-W

*2 DC SP

a solution of HF and HNO_3 to evaluate the N contents in the surface thin layer of HAZ. Besides other welds were etched by 10–20 μm of their surface in the same solution as above for SIMS analysis.

2.6 Test method

2.6.1 Measurement of N and O ion intensity by SIMS

The samples for SIMS analysis containing weld metal and HAZ as shown in Fig. 2 were prepared by machining from the welds one as welded and the others etched of the surface.

Cs^+ ions were irradiated on targets at HAZ as shown in Fig. 3 and the secondary ions, $^{90}Zr^{14}N^-$, $^{18}O^-$ and $^{90}Zr^-$ were collected and scanned by step-scanning process⁶⁾.

2.6.2 Chemical analysis on N in HAZ

Chemical analysis on N in HAZ was performed of the welds which were as welded and etched of its surface. The samples for chemical analysis were prepared by machining from the region near the weld fusion line and

Fig. 2 Sampling method of specimen for SIMS analysis.

Fig. 3 Direction of Cs^+ ion irradiation on HAZ.

Fig. 4 Sampling method of specimen for chemical analysis at HAZ.

outer half of wall thickness (W.T.) of tube as shown in Fig. 4. And N in those samples was analyzed by the inert gas melting-thermal conductivity method using LECO Type TC-436 Nitrogen and Oxygen Analyzer.

3. Experimental results and discussion

3.1 N depth profile by SIMS analysis and calculation

As reported in Report 1⁶⁾, N was absorbed highly at the surface in HAZ and diffused deep into inside at the region heated to β phase range (1,250–2,113 K) when P_{N_2} increased. Typical depth profiles of secondary ion intensity of $^{90}\text{Zr}^{14}\text{N}^-$ by SIMS analysis (abbreviated herein as $\text{Ii}[^{90}\text{Zr}^{14}\text{N}]$, incidentally it has been confirmed that $\text{Ii}[^{90}\text{Zr}^{14}\text{N}]$ was equivalent to N content in Zry-2⁹⁾) are as shown in Fig. 5. This figure shows $\text{Ii}[^{90}\text{Zr}^{14}\text{N}]$ depth profiles at the portion $L=1\text{ mm}$ (L : distance from fusion line, hereinafter shown as same) in HAZ welded in atmospheres with $P_{N_2}=8.0\text{ Pa}$ ($P_{O_2}=2.1\text{ Pa}$) at $P_T=0.10\text{ MPa}$ and $P_{N_2}=53.3\text{ Pa}$ ($P_{O_2}=13.9\text{ Pa}$) at $P_T=0.32\text{ MPa}$. It also shows $\text{Ii}[^{90}\text{Zr}^{14}\text{N}]$ depth profile at the portion $L=5\text{ mm}$ in HAZ welded in an atmosphere with $P_{N_2}=8.0\text{ Pa}$ ($P_{O_2}=2.1\text{ Pa}$) at $P_T=0.10\text{ MPa}$. That is, $\text{Ii}[^{90}\text{Zr}^{14}\text{N}]$ depth profile at the portion $L=5\text{ mm}$ heated within α phase range in HAZ was flat and on the same low level as in Zry-2 base metal (also in the case of $P_T=0.32\text{ MPa}$, $\text{Ii}[^{90}\text{Zr}^{14}\text{N}]$ depth profile at the portion $L=5\text{ mm}$ in HAZ was same as this). On the other hand, $\text{Ii}[^{90}\text{Zr}^{14}\text{N}]$ at the portion $L=1\text{ mm}$ heated to β phase range in HAZ was higher at its surface and decreased

exponentially with increase of the depth in both cases of $P_T=0.10$ and 0.32 MPa . And even at the portion of $18\text{ }\mu\text{m}$ deep inside, which is the maximum depth of detection (in this examination, it was made available to us to continue spattering by Cs^+ ion irradiation for a time to reach $18\text{ }\mu\text{m}$ deep inside), $\text{Ii}[^{90}\text{Zr}^{14}\text{N}]$ was on a higher level than that of Zry-2 base metal.

Therefore, here it was attempted to calculate the depth profiles of N diffused in HAZ containing portions still deeper than $18\text{ }\mu\text{m}$ based on the SIMS analysis values.

The concentration C (mass ppm) of N at a portion of x (cm) in depth from surface can be calculated by the equation (1) on the assumption that ① the diffusion of N in Zr alloy obeys the Fick's law, ② the diffusion coefficient of N in Zr alloy does not change by concentration of N, ③ there is no anisotropy on diffusion of N in Zr alloy and ④ concentration of N at the surface of HAZ does not change during the time heated to β phase range⁷⁻⁹⁾.

$$C - C_0 = (C_1 - C_0)[1 - \Phi(x/2\sqrt{Dt})] \quad (1)$$

where C_0 : Concentration of N in base metal (mass ppm), C_1 : Concentration of N at surface (mass ppm), x : Depth from surface (cm), D : Diffusion coefficient (cm^2/s), t : Time of diffusion (s).

To calculate concentration C of N at a portion x (cm) in depth in HAZ by equation (1), the value of diffusion coefficient D and concentration C_1 are needed.

The diffusion coefficient D was calculated as follows. As described in Report 1, the absorption and diffusion of N at HAZ in Zry-2 occurs at the β phase. The D of β phase Zr is given by equation (2)¹⁰⁾.

$$D = 1.5 \times 10^{-2} \exp\left(-\frac{30,700 \pm 1,000}{RT}\right) (\text{cm}^2/\text{s}) \quad (2)$$

In welding, the heating temperature at a certain portion is not constant but changes continuously in form of thermal cycle during welding. In that case, the mean value $\overline{Dt}$ has been determined integrally by dividing the time by n equally, and the calculated diffusion depth using this mean value $\overline{Dt}$ has been in good agreement with experimental diffusion depth of carbon into pure iron at a thermal cycle^{8,11)}. Although it has not been verified that the Dt determined by the same process as above was applicable or not for the calculation of diffusion of N into Zr alloy such as Zry-2, this process was taken to determine D assuming it was applicable in this study.

The mean value $\overline{Dt}$ of diffusion coefficient during welding cycles was determined by equation (3) simulating the above process.

$$\overline{Dt} = \frac{1}{n} \left\{ \int_{t_0}^{t_1} D_1(t) dt + \int_{t_1}^{t_2} D_2(t) dt \right. \\ \left. \dots + \int_{t_{n-1}}^{t_n} D_n(t) dt \right\} \quad (3)$$

where t_0 : time when temperature rose to β phase (1,250

Fig. 5 Typical depth profiles of $^{90}\text{Zr}^{14}\text{N}$ ion intensity in HAZ.

K), t_n : time when temperature fell down to α phase (1,250 K), $t_1, t_2 \dots t_{n-1}$: time divided t_0-t_n .

To calculate $\bar{D}t$ by equation (2) and (3) at the portion $L=1$ mm in HAZ dividing the time t_0-t_n by 10 ($n=10$) equally, $D_a=4 \times 10^{-7}$ cm²/s ($P_T=0.1$ MPa) and $D_b=2.7 \times 10^{-7}$ cm²/s ($P_T=0.32$ MPa) were obtained. Actually in the welding of tube with 0.9 mm thickness as shown in Fig. 1, though the thermal cycles at the portion $L=1$ mm in HAZ might not be completely same throughout the surface to back side, it was also assumed to be same in this study.

Besides, the concentration C_1 of N at the surface of HAZ was estimated from the value of SIMS analysis values as follows. $Ii[^{90}Zr^{14}N]$ at the surface of HAZ is not to be read clearly from Fig. 5, but $Ii[^{90}Zr^{14}N]$ at the portion of $X=1 \mu m$ (X is depth from surface, herein-after shown as same) can be read clearly. Though, the value of $Ii[^{90}Zr^{14}N]=1.43 \times 10^4$ (Arbit. unit, hereinafter shown as same) at the portion $L=1$ mm in HAZ was used as a standard value of this calculation. To convert $Ii[^{90}Zr^{14}N]$ into N concentration using an equation⁶⁾, $Ii[^{90}Zr^{14}N]=1.43 \times 10^4$ is equivalent to $N=1,525$ mass ppm. N concentration C_1 at the surface was calculated in reverse by the equation (1) substituting the value of $N=1,525$ mass ppm for C and $x=1 \mu m$ as follows.

$$C_1 = \{(C - C_0) / [1 - \Phi(x/2\sqrt{Dt})]\} + C_0$$

$$= \{1,493 / [1 - \Phi(1 \times 10^{-4} / 2\sqrt{4 \times 10^{-7} \times 5})]\} + 32$$

$$= 1,571 \text{ mass ppm}$$

where the previously calculated mean value $\bar{D}$ (4×10^{-7} cm²/s) and actual heating time t (5 sec) in β phase range were used. That is, the concentration of N at the surface of the portion $L=1$ mm in HAZ in the case of $P_T=0.10$ MPa shown in Fig. 5 was estimated to be 1,571 mass ppm. N concentration C at the portion of depth x

was calculated by equation (1) using this value as C_1 , and D and t as above.

Fig. 6 shows the relation between depth from surface and N concentration in HAZ in the case of $P_T=0.10$ MPa. This figure shows N depth profile of converted value from $Ii[^{90}Zr^{14}N]$ by SIMS analysis and calculated value based on the estimated value at the surface. The calculated value of N decreased rapidly from a high level at the surface toward the value of base metal (32 mass ppm) with increase of depth. The N concentrations were estimated to be 36 mass ppm at $60 \mu m$ deep inside and nearly equal to the value of base metal at $75 \mu m$ deep inside.

By same calculation process as above, the concentration C_1 of N at the surface of the portion $L=1$ mm in HAZ in the case of $P_T=0.32$ MPa shown in Fig. 5 was estimated to be 2,626 mass ppm. N concentration C at the portion of depth x was calculated by equation (1), using this value as C_1 , the previously calculated mean value $\bar{D}$ (2.7×10^{-7} cm²/s), and the actual heating time t (4.5 sec) in β phase range.

Fig. 7 shows the relation between depth from surface and N concentration in HAZ in the case of $P_T=0.32$ MPa. The calculated value of N decreased more rapidly from a high level at the surface toward the value of base metal with increase of the depth. The N concentrations were estimated to be 36 mass ppm at $50 \mu m$ deep inside and nearly equal to the value of base metal at $60 \mu m$ deep inside. Although the calculated value at the surface in Fig. 7 was much higher than that of Fig. 6, it decreased more rapidly and reached a low level as base metal at shallower portions. The result must have been brought about by the fact that the P_{N_2} in welding atmosphere was much higher (53.3 Pa) and absorbed much N

Fig. 6 Relation between depth from surface and nitrogen concentration in HAZ (1).

Fig. 7 Relation between depth from surface and nitrogen concentration in HAZ (2).

at near surface, while diffusion rate of N was lower because of their lower heating temperature and shorter heating time at the portion in HAZ in the case of $P_T = 0.32 \text{ MPa}$ as described in Report 1.

As the results above show, in both cases of Fig. 6 and Fig. 7, the N values converted from $\text{Li}[^{90}\text{Zr}^{14}\text{N}]$ were lower than that of calculated values near the surface and they approached each other as the depth increases. At present, the reason why of this difference at portions near the surface is still not clear.

3.2 N content in HAZ before and after surface etching

To evaluate N depth profile in HAZ, chemical analysis method was also applied. It was impossible to analyze N content directly in thin layers of HAZ as 10 or 20 μm in thickness, because sample making of such uniform thin thickness was very difficult and the quantity of sample was not enough for analysis, even if it could have been done by some other process. So, an alternative evaluation method, or an estimation of N depth profile in HAZ was applied, comparing the chemical analysis values of samples removed of its surface thin layers of 20 and 40 μm by etching with those of as welded samples.

Fig. 8 shows the relation between etched thickness at surface and N content in HAZ (at the portion shown in Fig. 4) of welds which were welded in atmospheres with various P_{N_2} at $P_T = 0.32 \text{ MPa}$. N in the outer half of W. T. in HAZ as welded increased with the increase of P_{N_2} . After the surface were etched by 20 and 40 μm, N in same portion as above of HAZ decreased to a level as low as the value of Zry-2 base metal. From the result, it was estimated that the N concentration in the surface layer is particularly high and most of the absorptions of N in HAZ should be limited to the thin layer of near

Fig. 8 Relation between etched thickness at surface and nitrogen content in HAZ.

surface in the case of welding condition of this study.

As N concentration was estimated by the calculation to 550 mass ppm at 20 μm deep inside and to 59 mass ppm at 40 μm deep inside in the case of $P_{N_2} = 53.3 \text{ Pa}$ ($P_T = 0.32 \text{ MPa}$) as shown in Fig. 7, a significant quantity of N must have diffused into 20 and 40 μm deep inside even in the case of $P_{N_2} = 25.2$ and 32.6 Pa ($P_T = 0.32 \text{ MPa}$). These effects did not appear on the analysis values for the N in analysis samples might have been homogenized by melting at the analysis examination.

N contents in outer half of weld metal removed by 20 and 40 μm of surface by etching were shown comparatively in Fig. 8. In the weld metals which were welded in the atmosphere of $P_{N_2} = 25.2$ and 32.6 Pa ($P_T = 0.32$

Fig. 9 Depth profiles of $^{90}\text{Zr}^{14}\text{N}$ ion intensity in HAZ after etched.

MPa), N contents were still on a higher level than base metal even removed of its surface up to $40\text{ }\mu\text{m}$. From these results it was made clear that N did not get into deep inside in HAZ which has not melted but heated just below the melting point (β -phase range) because it was taken into only through diffusion, while N got into deeper inside the weld metal because it was taken into not only by diffusion but also by convection of molten metal.

3.3 N depth profile by SIMS analysis after surface etching

Fig. 9 shows $\text{Li}[^{90}\text{Zr}^{14}\text{N}]$ depth profiles at the portion $L=1\text{ mm}$ in HAZ welded in an atmosphere with $P_{\text{N}_2}=38.6\text{ Pa}$ ($P_{\text{O}_2}=3.2\text{ Pa}$) at $P_{\text{T}}=0.32\text{ MPa}$ as welded and after etched of its surface by 20 and $40\text{ }\mu\text{m}$. Although $\text{Li}[^{90}\text{Zr}^{14}\text{N}]$ near the surface in HAZ as welded was on high levels same as the value shown in Fig. 5, $\text{Li}[^{90}\text{Zr}^{14}\text{N}]$ near the surface after etched by $20\text{ }\mu\text{m}$ has decreased and been found on a level as low as the value of base metal at approx. $5\text{ }\mu\text{m}$ in depth and deeper inside. After etched by $40\text{ }\mu\text{m}$, $\text{Li}[^{90}\text{Zr}^{14}\text{N}]$ has decreased to a level as low as the value of base metal at its surface.

Therefore, from this results it was also made clear that the diffusion of N was shallow and most of N did not get into deeper than $40\text{ }\mu\text{m}$ in HAZ in the case of above welding conditions.

3.4 O depth profile in HAZ

By the investigation with regard to O depth profile in HAZ by SIMS analysis, it has been made clear that O

Fig. 10 Depth profiles of ^{18}O ion intensity in HAZ after etched.

was absorbed mostly at the portion $L=3$ or 4 mm heated within α phase range rather than $L=1$ or 2 mm heated to β phase range as described in Report 1. And the diffusion depth was not as deep as with N, and estimated to extend only approx. to $5\text{ }\mu\text{m}$. Therefore, to make it clear, O depth profiles were taken at the most absorbed portion in HAZ after etched. Fig. 10 shows $\text{Li}[^{18}\text{O}]$ depth profiles at the portion of $L=3\text{ mm}$ in HAZ, welded in an atmosphere of $P_{\text{O}_2}=12.9\text{ Pa}$ ($P_{\text{N}_2}=1.3\text{ Pa}$) at $P_{\text{T}}=0.32\text{ MPa}$ and after etched by 10 and $20\text{ }\mu\text{m}$, comparing with as welded.

Both of the $\text{Li}[^{18}\text{O}]$ depth profiles were on a level as low as the value of Zry-2 base metal near the surface, and it was indicated that the depths of diffusion of O thereat were not deeper than $10\text{ }\mu\text{m}$, and O might form thin oxide layer with Zr in the case of comparatively low level of P_{O_2} as under the welding conditions of this examination.

4. Conclusion

Continued investigations were made on the depth profiles of nitrogen (N) and oxygen (O) absorbed in HAZ of ZrTN802D alloy (Zry-2) tubes by TIG welding in atmospheres with varied N_2 and O_2 partial pressures (P_{N_2} and P_{O_2}) at total pressures (P_{T}) of 0.10 and 0.32 MPa. The results obtained from these investigations are as follows:

(1) By the calculation of depth profile of N using the SIMS analytical values near the surface, it was made

clear that high concentration of 1,571 mass ppm of N at the surface in HAZ welded under a condition of $P_{N_2}=8.0$ Pa and $P_T=0.10$ MPa decreased rapidly toward the value of base metal with increase of depth and reached a low level nearly equal to the value of base metal at the portion of $75\text{ }\mu\text{m}$ in depth.

(2) Also high concentration of 2,626 mass ppm of N at the surface in HAZ welded under another condition of $P_{N_2}=53.3$ Pa and $P_T=0.32$ MPa decreased more rapidly toward the value of base metal with increase of depth and reached a low level nearly equal to the value of base metal at the portion of $60\text{ }\mu\text{m}$ in depth.

(3) Although there were some differences between SIMS analysis values and the calculated values at near surface, a tendency to approximate was observable of the two values as depth increased.

(4) As the N content in a part of the outside half of thickness of HAZ, after being etched of its surface by 20 and $40\text{ }\mu\text{m}$, became low in level same as with base metal even the HAZ had contained 60 to 80 mass ppm of N as welded, it was made clear, also from this result, that N had diffused into only thin layers near the surface in HAZ under the welding conditions of this examination.

(5) SIMS analysis was also made on the etched (20 and $40\text{ }\mu\text{m}$) surface of HAZ of a weld which indicated a higher level of N depth profile in HAZ as welded. The N depth profile on the etched ($40\text{ }\mu\text{m}$) HAZ was almost same as the base metal and it was further made clear also from this results, that the depth of diffusion of N was not deep.

(6) O depth profile in HAZ after being etched each by 10 and $20\text{ }\mu\text{m}$ of welds, which had indicated significantly high levels of O depth profile as welded, became low in level same as with the base metal. Thus it was estimated that O might form thin oxide layer at surface with Zr and did not diffuse deeper inside in the case of comparatively low level of P_{O_2} as under the welding

conditions of this examination.

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References

- 1) K. Komuro et al.: TIG Welding Phenomenon and Properties of Welds in Welding Atmospheres with Various Oxygen and Nitrogen Partial Pressures (Part 1), J. of Japan Weld. Soc., 12-2 (1994), 224-228.
- 2) K. Komuro et al.: Depth Profile of Oxygen and Nitrogen Concentration in Weld Metals by TIG Welding, J. of Japan Weld. Soc., 12-2 (1994), 229-235.
- 3) K. Komuro et al.: TIG Welding Phenomenon and Properties of Welds in Welding Atmospheres with Various Oxygen and Nitrogen Partial Pressures (Part 2), J. of Japan Weld. Soc., 12-3 (1994), 386-392.
- 4) K. Komuro et al.: Welding Atmosphere and Properties of TIG Weld Heat Affected Zone (Part 1), J. of Japan Weld. Soc., 12-3 (1994), 393-397.
- 5) L. Lunde: Special Features of External Corrosion of Fuel Cladding in Boiling Water Reactors, Nuclear Engineering and Design, 33 (1975), 178-195.
- 6) K. Komuro et al.: Depth Profile of Nitrogen and Oxygen absorbed in HAZ of ZrTN802D Alloy Tube by TIG Welding in Various Atmospheres (Report 1), J. of Japan Weld. Soc., 13-4 (1995), 491-499.
- 7) H. Suzuki et al.: Spot Welding of Zircaloy-2 Alloy Sheets, J. of Japan Weld. Soc., 30-6 (1961), 425.
- 8) H. Ikawa et al.: Diffusion Phenomenon of Carbon in Steel during Weld Thermal Cycles, J. of Japan Weld. Soc., 43-7 (1974), 650-660.
- 9) T. Naito: Actual Practices of Carbonizing Quenching, Nikkan Kogyo Shinbunsha (1979), 29.
- 10) B. Lustman et al.: The Metallurgy of Zirconium; McGRAW-HILL (1955), 422.
- 11) Y. Kikuchi: JIW BULLETIN 13, (1994), 34-37.