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# Hydrogen Embrittlement of SUS 316 Austenitic Stainless Steel Weldments†

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**Abstract**

*In order to understand the degrading behavior of hydrogen embrittlement of SUS 316 austenitic stainless steel weldment, base metal and welded joints which were welded with EBW and SMAW and heat-treated at 650°C–24hr for carbide and 850°C–6hr for Sigma-phase precipitation after welding were evaluated in tensile test at room temperature with and without hydrogen charging in the autoclave at 450°C–220atm–48hr treatment.*

*As a result the drastic degrading to 40% in reduction in area of the welded joint was observed when hydrogen of 41 ppm was contained in the welded joint of SUS 316 stainless steel.*

KEY WORDS: (Hydrogen embrittlement) (316 stainless steel) (GMAW) (EBW) (Weldment)

## 1. Introduction

SUS 316 (corresponding to AISI 316) austenitic stainless steel is one of proposed materials for fabrication of vacuum vessel in the experimental nuclear fusion reactor in Japan.

These vessels are fabricated with welding techniques of electron-beam- and arc-weldings today. It is considered, therefore, that the welded joint will be suffered with both repeated heat cycle and hydrogen penetration through an extreme high temperature plasma during operation. The authors are in great anxiety that the hydrogen embrittlement of the welded joint and sometimes the hydrogen induced cracking by additions of the residual stress welded and the external stress loaded occur in the construction. In addition to the above the residual ferrite in the weld metal which is usually contained for the purpose of the prevention for solidification cracking during welding seems to accelerate the anxious behavior.

Meanwhile the hydrogen embrittlement of austenitic stainless steel has been considerably reported, but most of them reported for the result that the hydrogen content in steel was not so high. Moreover the investigation concerning the hydrogen embrittlement of welded joint have not been reported for SUS 316 within the authors' knowledge[1-2].

Therefore the authors have investigated the characteristics of the hydrogen embrittlement of SUS 316 welded joint with arc- (SMA) and electron-beam (EB)-weldings in which an excessive hydrogen contains, in order to obtain the useful data for the designer for stainless steel vessels.

## 2. Experimental Procedures

### 2.1 Materials and welding conditions used

Base metal used is 3.0 mm thick sheet of commercially used SUS 316 austenitic stainless steel. The chemical and mechanical properties are as follows; C:0.04%, Si:0.68, Mn:1.30, P:0.030, S:0.002, Ni:10.85, Cr:16.88, Mo:2.07 and YS:27 kgf/mm$^2$, TS:59 kgf/mm$^2$, El: 58%, HRB:78.

A couple of base metal which was cut to 75 mm in width x 500 mm in length was longitudinally welded with one pass bead by EBW and SMAW. EBW was applied for no root-gap joint with 140 kV-30 mA-100 cm/min in horizontal position without filler wire.

SMAW was done for a square butt joint with 1.0 to 1.2 mm root gap by D316, 3.2 mm diam electrode with 110–120 amp, 25–30 volt, 24 cm/min.

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### 2.2 Heat treatment and tensile test

After welding three different specimens were prepared, that is, as-weld, 650°C–24hrs holded and air cooled for carbide precipitation and 850°C–6hrs holded and air cooled for Sigma-phase precipitation treatment. In order to make understanding further for hydrogen embrittlement of austenitic stainless steels weldment the heat treatments used were considerably overacted comparing to actual heat cycle in operation.

Tensile specimens were machined as shown in **Fig. 1** after the treatments. Tensile testing was done with a constant tensile rate of 0.5 mm/min for the specimens with and without hydrogen charge.

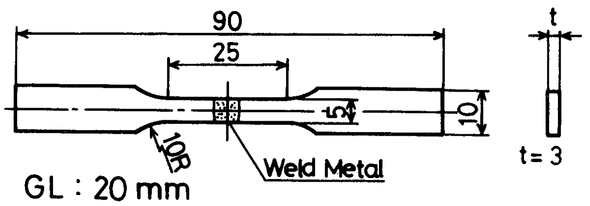



**Fig. 1** Tensile specimen used for welded joint and base metal

### 2.3 Hydrogen charging

The hydrogen charging of the specimens was done using autoclave under the following conditions: holded for 48hrs in 450°C and 220 atm of hydrogen, thereafter cooled to 150°C with 200°C/hr and to room temperature with 2 hrs. Moreover hydrogen analysis was done for the tensile specimens with and without hydrogen charge using Leco type analyser.

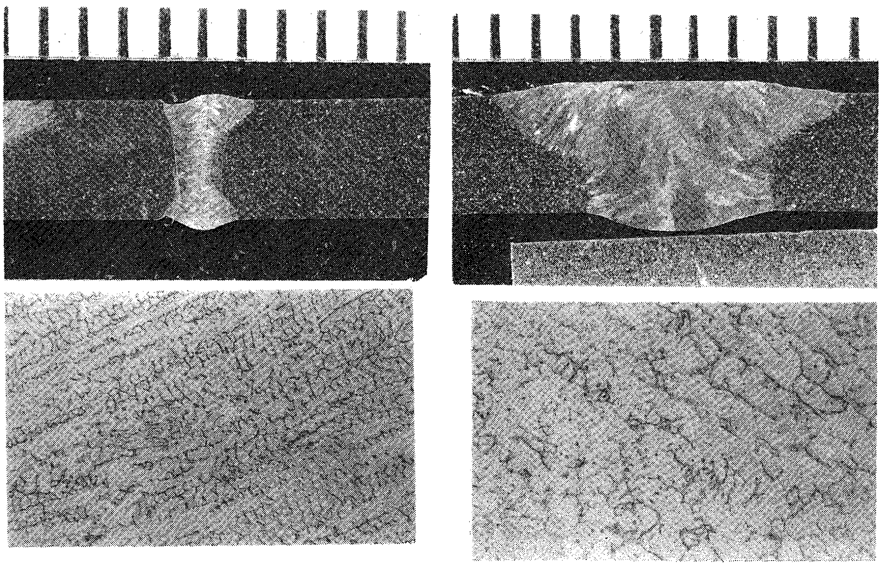
## 3. Experimental Results

### 3.1 Metallurgical investigation

**Figure 2 (a)** and **(b)** show macrostructure in crosssection of EBW and SMAW welded joints in the upper and microstructure of both weld metals in the lower. Ferrite scope indicated the residual delta ferrite in the weld and base metals as 1.9% for EBW, 6.6% for SMAW with D316 and 0.1% for base metal.

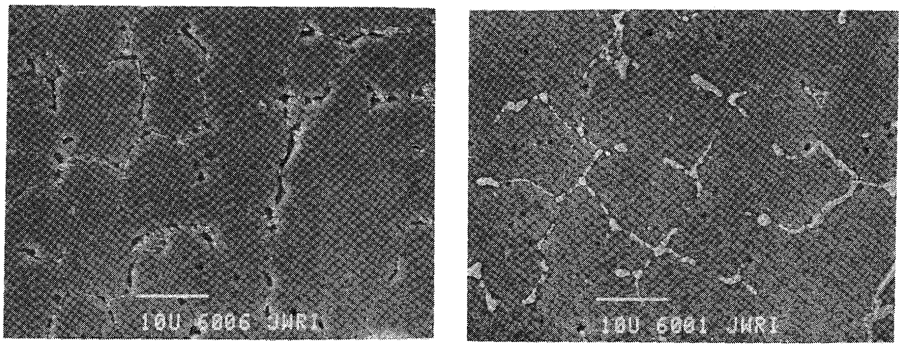
After the heat treatments the delta ferrite was changed to the fashions of carbide- and Sigma-phase precipitation which were typically shown in weld metal in **Fig. 3 (a)** and **(b)** respectively.

Average hydrogen contents in welded zone and base metal were shown in **Table 1**.



(a) (b)

**Fig. 2** Crosssectional macrostructure of welded joint and microstructure of weld metal in EBW and SMAW
(a) EBW (as-weld)
(b) SMAW (as-weld)



(a) (b)

**Fig. 3** Typical microstructure in weld metal with SEM (x2000) after heat treatment (1 $HNO_3$ : 3 HCl reagent)
(a) after 650°C–24hrs
(b) after 850°C–6hrs

**Table 1** Average hydrogen contents in welded zone and base metal measured with LECO type analyzer

| Specimen | Average hydrogen content (ppm) | |
|---|---|---|
| | Before H-charge | H-charged |
| EBW | 1 | 41 |
| SMAW | 3 | 41 |
| Base metal | 4 | 41 |

### 3.2 Tensile test investigation

**Table 2** collectively shows the tensile test results for base metal and EBW and SMAW weldments with and without hydrogen charge for different heat treatments. Note that hydrogenated specimens in as-weld condition have been heat-treated at 450°C as they were treated in autoclave. This treatment increased tensile strength of as-weld joint as a kind of precipitation hardening. The decrease in tensile strength (TS) in the specimen of 650°C HT and charged in SMAW is not explanable in this experiment. In the elongation (EL) and the reduction in area (RA) the values in all specimens were considerably decreased after hydrogen charge. Especially the decrease in RA is obvious. Now hydrogen Embrittlement Index (HEI)

**Table 2** Tensile tested results

| Welding (Electrode) | Heat treatment | Hydrogen charge | TS ($Kgf/mm^2$) | EL (%) | RA (%) | Fractured in* |
|---|---|---|---|---|---|---|
| Base metal (SUS316) | As Received | No | 61.5 | 82.0 | 77.6 | - |
| | | Yes | 60.5 | 73.2 | 67.1 | - |
| | 650°C (24hr) | No | 62.7 | 75.5 | 76.7 | - |
| | | Yes | 60.7 | 71.0 | 60.4 | - |
| | 850°C (6hr) | No | 63.0 | 77.7 | 70.4 | - |
| | | Yes | 60.0 | 74.0 | 58.2 | - |
| EBW (No filler) | As weld | No | 64.0 | 53.1 | 81.4 | FB |
| | | Yes | 68.4 | 51.1 | 48.5 | WM |
| | 650°C (24hr) | No | 65.3 | 53.2 | 66.3 | FB |
| | | Yes | 66.2 | 40.4 | 34.2 | FB |
| | 850°C (6hr) | No | 64.7 | 53.1 | 74.2 | WM |
| | | Yes | 66.0 | 42.3 | 34.4 | FB |
| SMAW (D316) | As weld | No | 60.4 | 42.3 | 60.1 | WM |
| | | Yes | 67.7 | 34.3 | 34.1 | WM |
| | 650°C (24hr) | No | 69.3 | 27.8 | 44.2 | WM |
| | | Yes | 60.5 | 25.1 | 31.3 | WM |
| | 850°C (6hr) | No | 60.1 | 36.4 | 34.1 | WM |
| | | Yes | 59.6 | 25.9 | 23.6 | WM |

* FB:Fusion boundary, WM:Weld metal
Crosshead speed:0.5 mm/min

in RA was defined as $[(RA_O-RA_X)/RA_O] \times 100$ in percent, where $RA_O$ is the value of reduction in area in non-HT and non-hydrogen charged specimen for base metal, EBW joint or SMAW joint, and $RA_X$ is that in the treated specimen. Therefore the HEI means the loss of reduction in area.

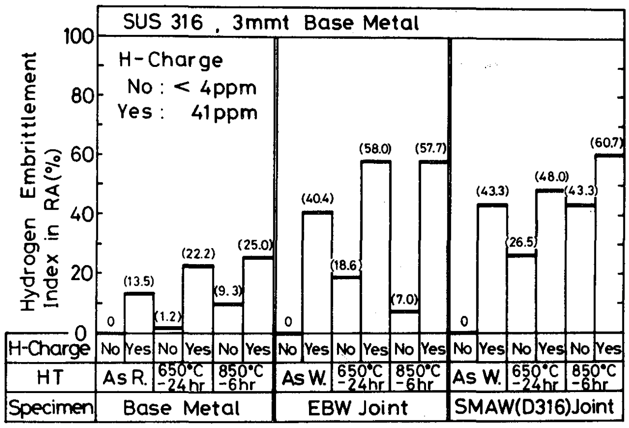
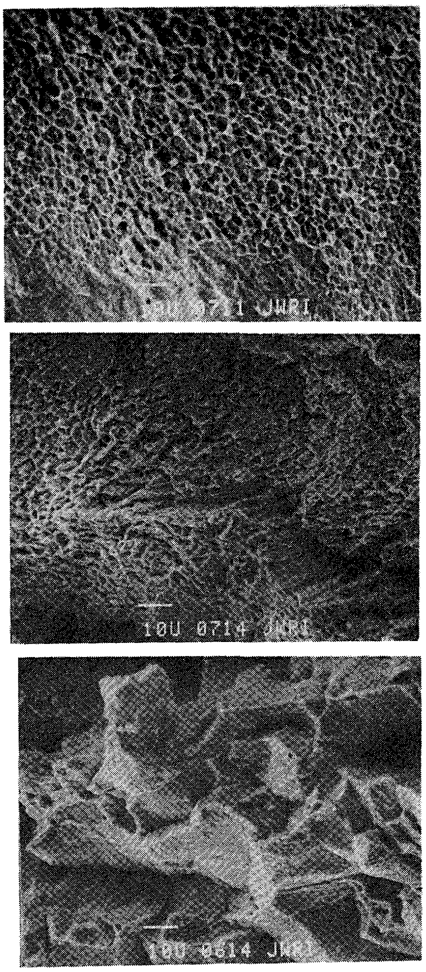



**Fig. 4** Effects of heat treatments and hydrogen charge on hydrogen embrittlement index in the reduction in area of the tensile tested specimen for base metal and EBW and SMAW joints

The HEI is shown in **Fig. 4** for base metal, EBW joint and SMAW joint. For base metal only heat treatment without hydrogen charge was not so large in the HEI, but after heat treatment and hydrogen charge the HEI showed about 22 to 25%, which means about 78 – 75% ductility comparing that in as-received and no charged specimen. However the ductility loss was much obvious in the welded joints. Hydrogenated specimen in as-weld condition in both welded joints showed fairly loss in RA as about 40 to 43% in the HEI. Moreover after heat treatments hydrogenated specimens showed considerably loss in RA as about 48 to 60% in the HEI. This means that the ductility was decreased to 40% in minimum as compared with the original ductility. In SMAW joint only heat treatments of 650°C and 850°C showed the fair decrease in ductility which seems to be larger amount of delta ferrite.

Fractographic investigation was taken for the fractured specimens. **Figure 5** showed near center of the fractured surface of EBW specimen with SEM. **(a)**, **(b)** and **(c)** showed as-weld and without hydrogenated, 650°C–24hrs and without hydrogenated and 650°C–24hrs and hydrogenated specimens, respectively. Typical dimple pattern in (a) changed to dimple pattern with secondary cracks in (b) which decreased to about 80% in ductility. Moreover by the addition of hydrogen about 41ppm the fracture changed to intergranular surface as in (c). The fracture mode also showed a considerable loss in ductility.




(a)

(b)

(c)

**Fig. 5** Fractographic investigations of center of fractured surface of tensile tested specimen of EBW joint
(a) As-weld and no H-charged
(b) 650°C–24hrs and no H-charged
(c) 650°C–24hrs and H-charged (41 ppmH)

## 4. Conclusions

The hydrogen embrittlement of base metal and welded joints of SUS 316 with EBW and SMAW was investigated in this report. As a result the following conclusions were drawn;

1) The hydrogen embrittlement occurred in both welded joints by penetration of hydrogen. The degree of the embrittlement was much severe in heat treated conditions of carbide- and Sigm-precipitation treatments than in as-weld condition.
2) The hydrogen embrittlement revealed extremely in the reduction in area, and nextly in the elongation of tensile test specimen.
3) When the reduction in area of the hydrogenated tensile test specimen (41 ppm) was compared with that without hydrogen, the reduction in area for both welded joints was decreased to about 60% in as-weld condition, and about 40% in heat treated condition. How-

ever it of base metal was about 86% in as-received and about 75% in heat treated condition.

4) Fractographic investigations also indicated the embrittlement of the joint by the addition of hydrogen. Fracture surface changed from dimple to intergranular mode with hydrogen.

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