Improving Electron Beam Weldability of Heavy Steel Plates for PWR-Steam Generator

Yukio TOMITAt, Hidesato MABUCHI and Kunio KOYAMA

Steel Research Laboratory, Nippon Steel Corp.*

(Received March 11, 1996)

Installation and replacement of many PWR-steam generators are planned inside and outside Japan. The steel plates for steam generators are heavy in thickness, and increase the number of welding passes and prolong the welding time. Electron beam welding (EBW) can greatly reduce the welding period compared with conventional welding methods (narrow-gap gas metal arc welding (GMAW) and submerged arc welding (SAW)). The problems in applying EBW are to prevent weld defects and to improve the toughness of the weld metal. Defect-free welding procedures were successfully established even in thick steel plates. The factors that deteriorate weld-metal (WM) toughness of EBW were investigated. The manufacturing process, which utilizes a new secondary refining process at steelmaking and a high-torque mill at plate mill in actual mass-production, were established. EBW base metal and WM have better properties including fracture toughness than those of conventional welding processes. As a result, an application of EBW to the fabrication of PWR-steam generators has become possible. Large amounts of ASTM A533 Gr B Cl 2 (JIS SQV2B) steel plates in actual PWR-steam generators have come to be produced (more than 1,500 ton) by applying EBW.

KEYWORDS: PWR type reactors, steam generators, electron beam welding, heavy steel plate, narrow-gap gas metal arc welding, submerged arc welding, weld metal, welding defect, toughness, fracture toughness, weldability

I. INTRODUCTION

Many of the steel plates used for PWR-steam generators are heavy in thickness (up to 120 mm). Such heavy steel plates increase the number of welding passes and prolong the welding time when welded by conventional welding. The number of welding passes may be reduced to shorten the welding time, which in turn increases the welding heat input. The heat input cannot be increased for PWR-steam generators, because of resultant loss of toughness. The number of welding passes may be also reduced by narrow-gap welding(1), but there is a limit to the reduction in the number of welding passes.

Electron beam welding (EBW) can weld heavy steel plates in a single pass and features high welding efficiency for heavy steel plates, while conventional welding increases in the number of passes with increasing plate thickness. EBW was compared with gas metal arc welding (GMAW) and submerged arc welding (SAW) in terms of cost and plate thickness(2). EBW is advantageous in the welding of steel plates with a thickness of 50 mm or more. There are many plans to install or replace PWR-steam generators. EBW will become a powerful tool for the fabrication of PWR-steam generators. 

Several efforts have been made to improve the toughness of ASTM A 533 Gr B Mn-Mo-Ni steel plates for PWR-steam generators(1)(3)-(6). No such studies are made on electron beam welds of these steel plates.

The problems in applying EBW are to prevent weld defects and to improve the toughness of the weld metal. Weld metals of EBW is featured of its narrow width and the allowance for joint accuracy is limited. Accordingly any deviation of the location of electron beam impingement may lead to weld defects. A number of research works have been made on butt-welding of thick plates(7)(8). However the actual joints in practical structures are complicated; not only the simple butt-joint, but also of other types of corner joint, T-joint or joints with other attachments.

Secondly conventional welding melts the weld metal and part of the base metal by feeding welding materials, and thereby joins the weld metal and base metals. The toughness of welds is improved by using high-nickel welding materials, for instance. EBW melts, solidifies, and joins steel plates without using welding materials. EBW is characterized by rapid heating and cooling cycles(9). The toughness of electron beam welds may deteriorate, depending on the chemical composition of steel plates. This paper describes the analysis of factors controlling the deterioration in the toughness of electron beam welds and the development of meth-
methods for improving the toughness of electron beam welds. The paper also presents the excellent electron beam weld toughness obtained when EBW was applied to the welding of up to 120 mm thick ASTM A 533 Gr B Cl 2 steel plates for PWR-steam generators.

II. WELDING PROCEDURE INVESTIGATION

1. Groove Configuration and Lack of Fusion

Since weld metals of EBW is featured of its narrow width, any deviation of the location of beam impingement may lead to a lack of fusion. Figure 1 shows the effects of beam deviation and root opening on the occurrence of lack of fusion in the case of corner joint welding of 65 mm thick plates under the welding condition of 100 kV, 300 mA and 30 cm/min with the beam oscillation of 2 mm. The base metal is ordinary steel. As shown in Fig. 1, it is necessary to keep the beam deviation within 0.5 mm and the root opening less than 0.5 mm in order to attain satisfactory fusion. A root opening greater than 0.5 mm causes undercut due to the shortage of molten metals, which may be compensated by using the filler metal addition. For the sake of safety, a control of root opening should be maintained by proper edge preparation and tack welding.

2. Prevention of Flow-out of Molten Metal

Flow-out of molten metals occurs more frequently in welding corner joints than butt-welding. It may be attributed to the increased fusion of the flange plate in corner joints due to the deviation of beam impingement location. A strict control of beam deviation is necessary. The residual magnetism in the base metal is well recognized to cause the EBW beam to deviate. In the present investigation, it was ascertained that the residual magnetism should be controlled to a level less than 0.005 T or desirably, less than 0.001 T. As a countermeasure, shielding of the beam path from stray magnetic flux proved in the present investigation, to be very effective in preventing the beam from deviating.

3. Prevention of Porosity Formation

A number of reports have been published on the EBW porosity formation in steel welding; namely the effect of beam focusing and oscillation amplitude, the effect of beam oscillation, the effect of the chemical composition of steels, etc. The contents of nitrogen and oxygen in steels are requested to be controlled less than 150 mass ppm, to prevent porosity in EBW. The contents of them in the current structural steels are usually less than 100 mass ppm. However manual active welding (MAW) tack welded portions contained high oxygen and nitrogen that led to the porosity formation. Metal arc gas (MAG) tack welded portion also caused porosity. On the contrary, tack welded portions by GMAW or 20 vol% CO2-Ar arc welding produced no porosity. From those results, it was concluded that the oxygen content in a tack weld metal should be less than 200 mass ppm to prevent porosity formation because of the difficulty of decreasing the oxygen content less than 200 mass ppm.

III. METALLURGICAL ASPECTS

1. Analysis of Factors Controlling the Deterioration in Toughness of Electron Beam Welds

To solve the problem of reduced toughness of electron beam welds, factors controlling the deterioration of toughness were analyzed prior to the application of EBW to heavy steel plates for PWR-steam generators. The factor analysis involved the microstructural and fractographic observation of fracture initiation and propagation regions in Charpy impact test specimens.

(1) Microstructural Examination

The fracture surface near the fracture initiation in each of two Charpy impact test specimens, one with low energy value and the other with high energy value, was examined under the scanning electron microscope. The resultant scanning electron micrograph is shown in Fig. 1.
Photo. 4. There are more microcracks than those observed on the pre-etch microstructure of Photo. 3. These micrographs show that there are microcracks directly visible on the fracture surface and that there also are microcracks not visible but located right beneath the fracture surface. Photo. 5 shows a cross-sectional microstructure just below the fracture initiation. The microstructure is upper bainite mixed with lower bainite. Microsegregation which was probably produced as the electron beam weld solidified is continuously connected in some region. A large microcrack is along the microsegregation. The microsegregation is present connected at the tip of the microcrack, and fragments of it are left along the microcrack. This suggests that the microcrack opened because of solidification segregation at the dendrite interface.

(3) Intergranular Cracking from Intergranular Segregation

The scanning electron micrograph, Photo. 6, shows intergranular cracking on the fracture surface of the low-energy value Charpy impact test specimen. This is probably due to the tearing off of the dendrite interface where the grain-boundary segregation of impurity elements exists. Intergranular cracking from intergranular segregation is considered to accelerate the fracture propagation.

It was found as a result that the toughness of EBW is reduced as follows:

(1) Upper bainite is present as microstructural constituent.

Photo. 1 Microstructure of fracture initiation site in low-energy value Charpy impact test specimen

Photo. 2 Microstructure of fracture initiation site in high-energy value Charpy impact test specimen

Photo. 3 Scanning electron micrograph of fracture initiation site in Charpy impact test specimen

Photo. 4 Scanning electron micrograph of region just below fracture initiation

Photo. 5 Microstructure of region just below fracture initiation
The fracture originates from a microcrack along solidification segregation.

(3) The fracture propagation is accelerated by intergranular cracking from intergranular segregation.

2. Improving Toughness of Electron Beam Welds

Methods for improving the toughness of electron beam welds were studied, based on the analysis of factors responsible for the deterioration in the toughness of electron beam welds discussed in Sec.II-1. As listed in Table 1, the compositional range of each element was determined, based on the requirements of ASTM A533 Gr B Cl 2 steel plates for PWR-steam generators. EBW conditions were selected to simulate the cooling rate in 15 to 55 s from 800 to 500 °C. Through bead on plate welding was performed under the selected conditions. The EBW joints were then given long postweld heat treatment (PWHT). The center of each electron beam weld was microstructurally observed and examined for microsegregation by a computer-aided electron-probe microanalyzer (CMA). The fracture initiation and cross-sectional microstructure of Charpy impact test specimens were observed under the scanning electron microscope.

(1) Microstructural Control

To decrease the volume fraction of upper bainite and increase that of lower bainite, it is necessary to increase hardenability intensifiers, such as chromium, nickel and molybdenum. Figure 2 shows the effects of chromium and nickel contents on the toughness of electron beam welds. The toughness of electron beam welds improves with increasing chromium and nickel contents of the hardenability intensifiers. When the electron beam weld is of the upper bainite microstructure, its toughness can be improved if the carbon content is reduced. Figure 3 shows effect of the carbon content on the toughness of electron beam welds. If the carbon content is reduced to 0.18 mass% and then to 0.16 mass% from the level of 0.20 mass% in ASTM A533 Gr B Cl 2 steel plates, the toughness of electron beam welds improves. Grain refining is also effective in improving the toughness of electron beam welds. Figure 4 shows the effect of nitrogen content on the toughness of electron beam welds. The toughness of electron beam welds can be improved if nitrogen content is lowered to 50 mass ppm from the level of 80 mass ppm usually observed in ASTM A533 Gr B Cl 2 steel plates.

The cooling rate in the EBW heat cycle increases as the weld bead width decreases. Figure 5 shows the effect of the weld bead width on the cooling time from

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>Al</th>
<th>Ti</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10-0.21</td>
<td>0.19-0.33</td>
<td>1.36-1.45</td>
<td>0.001-0.009</td>
<td>0.001-0.002</td>
<td>0.15-0.60</td>
<td>0.55-0.65</td>
<td>0.65-1.50</td>
<td>0.018-0.080</td>
<td>0-0.010</td>
<td>0.0035-0.0096</td>
</tr>
</tbody>
</table>

Table 1 Chemical composition ranges of the steels (mass%)
800 to 500°C and equivalent heat input \( (9) \), and the microstructures of the center of electron beam welds for bead widths of 6 and 4 mm. As the bead width decreases from 6 to 4 mm, the cooling time from 800 to 500°C sharply decreases from 40 to 18 s. As the cooling time decreases or the cooling rate increases, the volume fraction of lower bainite in the electron beam weld increases. Figure 6 shows the influence of the weld bead width on the toughness of electron beam welds. The toughness of electron beam welds improves with decreasing weld bead width. By decreasing the weld bead width to 5 or 4 mm, the cooling rate increases and the weld toughness improves.

Figure 7 summarizes the aforementioned influences of alloying elements and weld bead width on the toughness of electron beam welds.

(2) Reduction in Solidification Segregation by Reduction in Phosphorus Content

Low-phosphorus \( (P=0.002 \text{ mass\%}) \) and medium-phosphorus \( (P=0.006 \text{ mass\%}) \) steels were examined for solidification segregation. Photo. 7 shows the microstructure of the center of an electron beam weld of each steel as examined by using nital etch. The medium- and low-phosphorus steel in which the matrix is a mixture of lower and upper bainite are clearly different in the solidification segregation at the dendrite interface. In the medium-phosphorus steel, the solidification segregation is almost continuously connected, and the segregation zone spacing is narrow. Whereas in the low-phosphorus steel, the solidification segregation is locally scattered, and the segregation zone spacing is wide. For a further study on the solidification segregation, 0.5 mm square area at the center of each electron beam weld was examined by CMA for the segregation of phosphorus and other elements; manganese, nickel and molybdenum contained in large amounts in this type of steel. The segregation of phosphorus is clearly visible along the dendrite interface in the medium-phosphorus steel, but is scattered and observed little in the low-phosphorus steel. The segregation of the other elements; manganese, nickel and molybdenum is continuously connected along the dendrite interface in the medium-phosphorus steel and is discontinuous in the low-phosphorus steel. The following may be said from the above discussion:

(a) The low-phosphorus steel has the solidification segregation of phosphorus reduced along the dendrite interface.

(b) The low-phosphorus steel has the segregation of manganese, nickel and molybdenum also reduced along the dendrite interface.

(3) Reduction in Intergranular Segregation by Reduction in Phosphorus Content

Scanning electron micrographs were taken in eight fields in the direction of fracture extension from the bottom of the notch, including the fracture initiation, in each of the Charpy impact test specimens made of the low-phosphorus and medium-phosphorus steels and notched at the center of the electron beam weld. The intergranular fracture surface area fraction of the region was determined from the scanning electron micrographs.
Figure 8 shows the relationship between the intergranular fracture surface area fraction and Charpy absorbed energy value. The low-phosphorus steel has intergranular fracture surface area fractions of 0.7 and 0.9% for absorbed energy values of 104 and 49 J, respectively. The medium-phosphorus steel has intergranular fracture surface area fractions of 3.4 and 3.6% for absorbed energy values of 23 and 19 J, respectively. In other words, the reduction in the phosphorus content reduces the intergranular fracture surface area fraction in the region of fracture propagation around the fracture initiation.

As discussed above, the reduction in the phosphorus content is considered to reduce the microsegregation of phosphorus at the dendrite interface and the microsegregation of manganese, chromium, and nickel contained in large amounts; to inhibit the occurrence of microcracks around and just below the Charpy impact fracture initiation because of the microsegregation; to reduce intergranular fracture in the stages of fracture initiation and propagation; and to improve the toughness of electron beam welds. It is difficult to think that intergranular fracture is a chief factor because the maximum fracture surface area fraction of 3.6% is relatively small. The prevention of microcracks by reduction in solidification segregation is considered as a factor mainly controlling the improvement in the toughness of electron beam welds when the phosphorus content is lowered.

It may be thus concluded that solidification segregation and intergranular segregation which are characteristics of electron beam welds irrespective of steel grades must be both reduced to improve the toughness of electron beam welds. One means to this purpose is the reduction of the phosphorus content.

IV. PRODUCTION PROCESS

The production process is schematically illustrated in Figure 9. The contents of impurity elements like phosphorus, sulfur, and oxygen are reduced to the lowest possible limits by the combination of LD converter steelmaking and ladle refining. In the rolling stage, steel plates are rolled on high-torque mills with high shape factor and sound quality to their thickness center despite their large thickness.

V. PROPERTIES

1. Properties of Steel Plate

ASTM A533 Gr B Cl 2 steel plates for PWR-steam generators were produced, based on the above study results. The chemical composition of the steel plate is given in Table 2. Table 3 lists the tensile, Charpy impact, and drop weight test results of specimens after quenching and tempering (at 660°C) and post weld heat treatment (at 615°C for 10 h). The steel has sufficient strength, toughness, and drop weight properties.
2. Properties of Electron Beam Welds

EBW conditions are given in Table 4. The target weld bead width was 4 mm. Electron beam welds were made in a conventional single pass as well as in four passes in consideration of repair welding by cross welding. The macrostructures of single-pass and four-pass EBW joints are shown in Photo. 8. The hardness distribution of EBW joint is shown in Fig. 10. Maximum hardness is about 260.

Table 5 shows the Charpy impact test results of specimens notched at the center of the weld metal or at the fusion line (FL). Irrespective of single-pass or four-pass EBW joints, good energy values of over 200 and 100 J are obtained at test temperatures of -23°C and of -40 and -50°C, respectively. Table 6 shows the drop weight test results of specimens notched at the center of the weld metal and at the fusion line (FL). Irrespective of notch location, the specimens exhibit a good value of
3. Comparison of EBW with Conventional Welding Processes

The welding test results by the EBW process of ASTM A533 Gr B Cl 2 steel plates are compared with those by conventional welding processes\(^1\). Table 7 compares the EBW process and the conventional SAW and GMAW processes in welding test results. The data of Table 6 show that the EBW process provides properties equivalent to or better than those obtained from the conventional welding processes.

VI. RESULTS OF MANUFACTURE OF A533 Gr B Cl 2 STEEL PLATES

1. Tests to Demonstrate Fracture Toughness of A533 GrB Cl 2 Steel Plates (Equivalent to JIS SQV2B)

In the manufacture of 4-loop type PWR steam generators of 1,150 MW or more, A533 Gr B Cl 2 steel plates (tensile strength: 620 N/mm²) that have a higher strength than A533A Cl 1 (JIS SQV2A) steel plates (minimum tensile strength: 550 N/mm²) for the conventional 2-loop or 3-loop type steam generators are used by Japanese plant makers, thereby preventing an increase in plate thickness. A533 Gr B Cl 2 steel plates are also used in 2-loop or 3-loop steam generators for replacement that have recently been manufactured. According to the Electrotechnical Requirement 4206 of the Japan Electrotechnical Association (JEAC) that is referred to in Notification No.501 of the Ministry of International Trade and Industry, to use steel plates with the minimum yield point exceeding 340 N/mm², such as A533 Gr B Cl 2, in steam generators, it is necessary to demonstrate by conducting a dynamic fracture test of plates from three heats that values of fracture toughness obtained are not less than the right side [hereinafter called \(K_{IR}\) referred to fracture toughness (the equation below)] of the inequality shown in Paragraph 5, Sub-section 1, Section 4 of the Notification No.501: \(K_{IR} = 29.43 + 1.34 \exp\left[0.0261 (T - R_{NDT} + 88.9)\right]\)

Dynamic and static fracture toughness tests of the base metal and weld heat-affected zone of the A533 Gr B Cl 2 steel plates (plate thickness: 88, 97, 100 and 120 mm) were conducted. The results of the tests are shown in Figs. 11 and 12. As is apparent from the figures, it was ascertained that the fracture toughness test values (\(K_I\) and \(K_{II}\)) of the base metal and weld fully meet the \(K_{IR}\) curve specified in Notification No.501.

VII. CONCLUSIONS

As many PWR-steam generators for nuclear power plants are to be newly installed or replaced inside and outside Japan, there is demand for shortening the welding time of heavy steel plates used as material of construction for PWR-steam generators. The EBW process was studied for use in this application. A serious obstacle to this application of the EBW process was welds defects and deterioration in the toughness of resultant welds. Successful defect-free welding procedures were established for thick steel plates. As for weld toughness, factor analysis identified the following as causes for the reduced toughness of electron beam welds;

1. Upper bainite as microstructural constituent
2. Microcracks along solidification segregation as fracture initiation
Fig. 11 Dynamic fracture toughness of A533 Gr B Cl 2 steel plates for steam generators

Fig. 12 Dynamic fracture toughness of A533 Gr B Cl 2 steel plates welds for steam generators
(3) Fracture propagation as intergranular cracking accompanying intergranular segregation.

Electron beam welds of excellent toughness were obtained after microstructural control and reduction in solidification segregation and intergranular segregation by reduction in the content of phosphorus. Based on the study results, up to 120 mm thick steel plates were manufactured according to the ASTM A533 Gr B Cl 2 (JIS SQV2B) requirements and investigated for EBW properties. The electron beam welds thus made have properties equivalent to or better than those of welds made by the conventional SAW and GMAW welding processes. These excellent weld properties help to achieve the sharp reduction in the time required for welding heavy steel plates for PWR-steam generators. As a result, application of EBW to the fabrication of PWR-steam generators has become possible and large amounts of ASTM A533 Gr B Cl 2 (JIS SQV2B) steel plates for EBW in actual PWR-steam generators (more than 1,500 ton) have come to be produced.

REFERENCES