Hitachi's Activities for Suppression of Stress Corrosion Cracking

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OVERVIEW: Stainless steel and nickel-based alloys are used in key equipment in BWRs, including reactor internals. Examples of SCC have been experienced in both materials. Because measures for dealing with SCC are an important issue for coping with aging plants, Hitachi has for many years been working on techniques for preventing SCC initiation and applying these techniques in actual plants. Recent measures for dealing with SCC have included identifying the factors leading to non-sensitized SCC and confirming the effectiveness of countermeasures. Development is also proceeding on new materials that can minimize SCC, including work on evaluating SCC characteristics such as the collection of data on SCC crack growth rates, information which is required when evaluating the integrity of structural components in plant equipment. Along with confirming the effectiveness of techniques such as removing the cold-worked layer, grain-boundary-character-controlled materials which are expected to inhibit SCC are also being developed. Development is also underway on using laser welding to achieve high quality and high efficiency welding, and the technique's effectiveness at improving SCC performance is being tested.

INTRODUCTION

STAINLESS steel and nickel-based alloys are used in recirculation piping and reactor internals at BWR (boiling water reactor) power plants. Although these

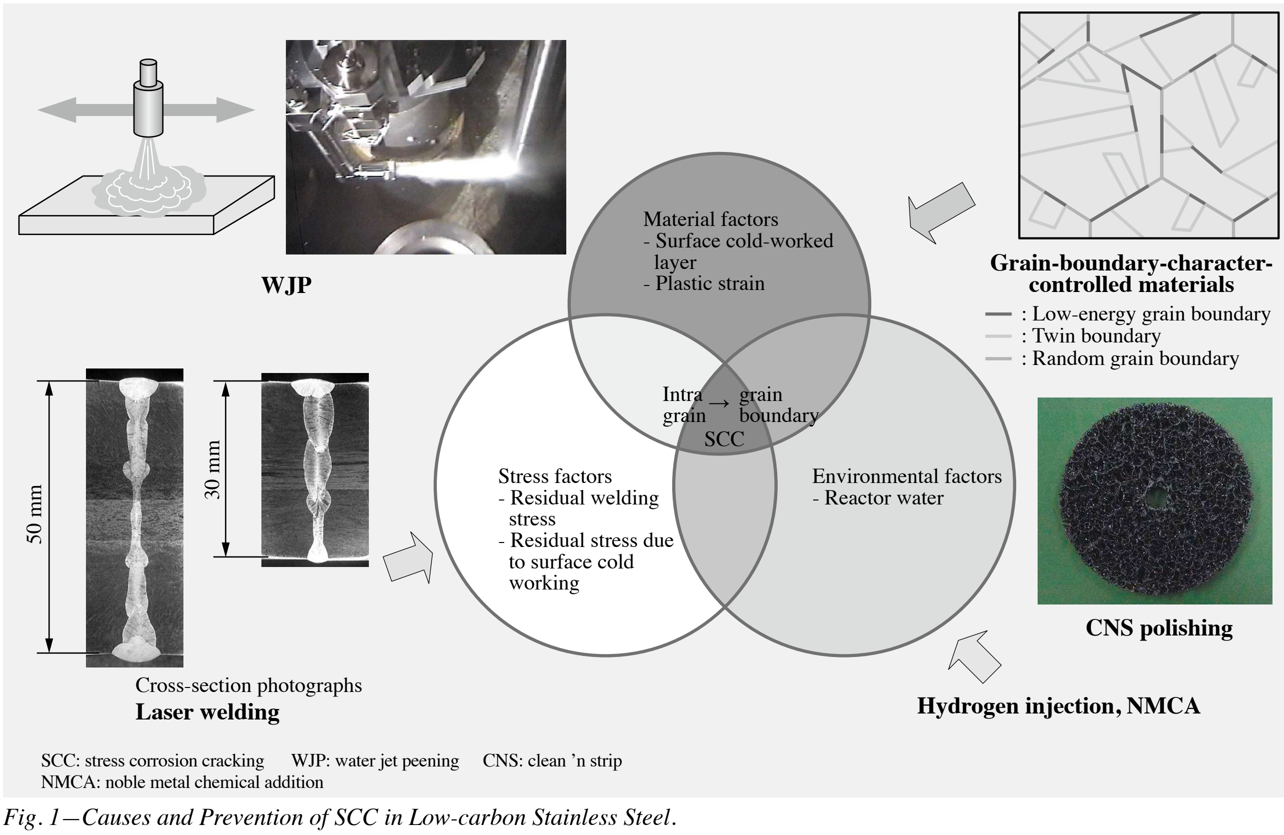

Fig. 1—Causes and Prevention of SCC in Low-carbon Stainless Steel.
The causes and associated countermeasures for SCC are shown.

materials produce few corrosion products and have excellent strength properties, they are subject to SCC (stress corrosion cracking) at locations subject to high tensile stress under the conditions that apply in the reactor water of BWRs. For this reason, finding ways to counter SCC is an important issue for coping with aging plants and Hitachi has for many years been working to inhibit SCC initiation by developing techniques that approach the problem from the perspectives of the materials used, their environment, and the stresses to which they are subject.

This article looks at how the factors behind SCC are identified and improvements in materials made. It describes the effects of the cold-worked layer, the techniques for countering these effects, and the development of new materials. In the area of improvements to manufacturing processes, the article also details progress in the development of laser welding (see Fig. 1).

IDENTIFICATION OF FACTORS BEHIND SCC AND IMPROVEMENTS IN MATERIALS

Background to the Development of Preventative Maintenance Techniques

After incidents in the 1970s of SCC occurring in stainless steel pipes due to the sensitizing of regions affected by the heat of welding (chrome depletion at grain boundaries due to the precipitation

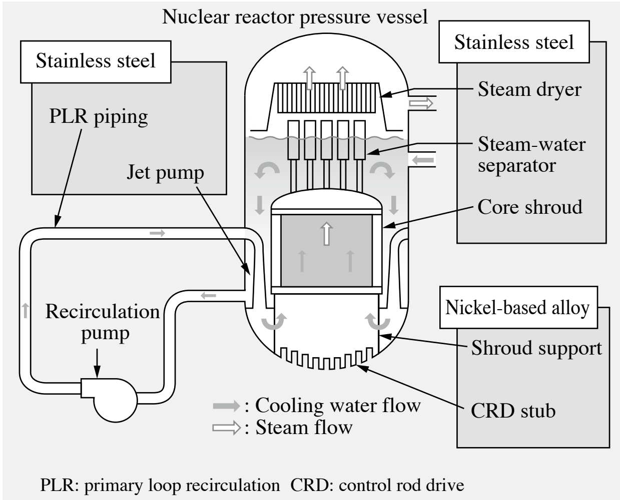

Fig. 2—Main Parts and Materials Used in BWR Power Plant.
The materials used in the main BWR (boiling water reactor) parts are shown.

of chromium carbides), low-carbon stainless steel and nickel-based alloys stabilized by the addition of niobium were developed to counter SCC and were adopted in plants from the 1980s onwards (see Fig. 2).

Since 2001, however, SCC that is not associated with sensitization has been found in core shrouds and recirculation piping made of low-carbon stainless steel. To counter this problem, techniques including the removal of surface cold working and stress improvement have begun to be adopted.

In response to this situation, Hitachi has been

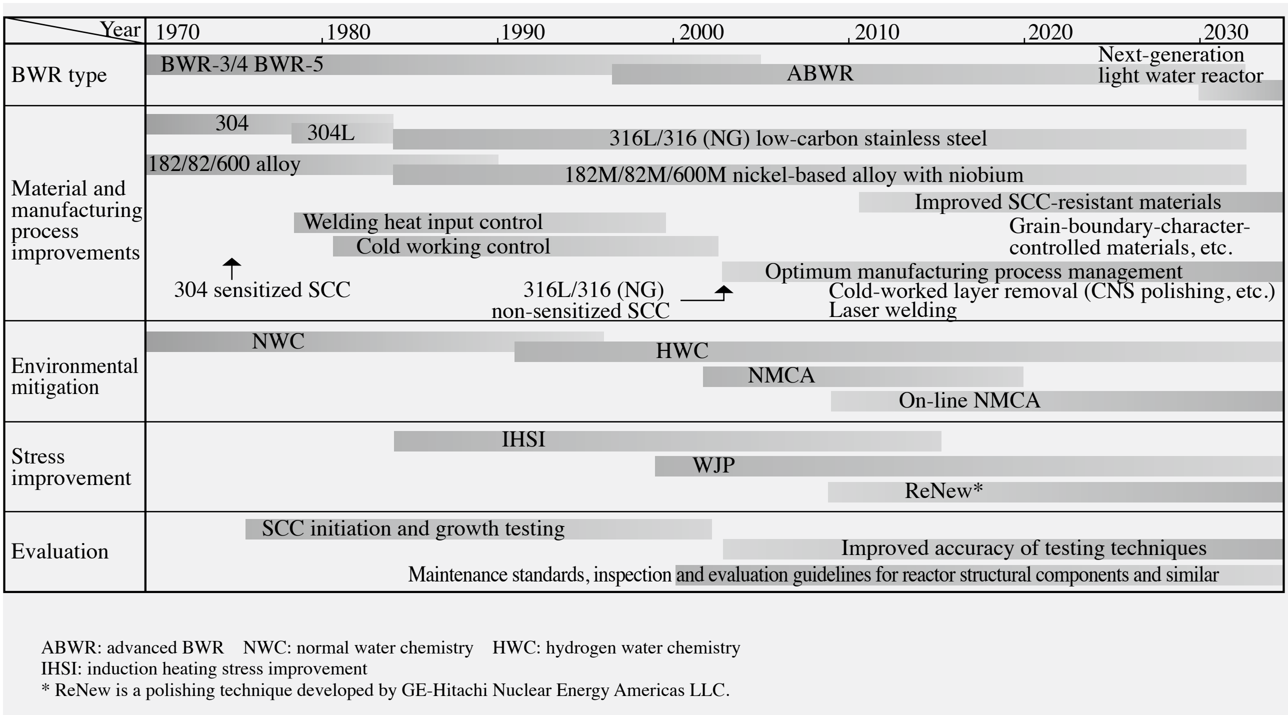

Fig. 3—Background to SCC Countermeasures in BWR Plant Materials.
The history of measures for dealing with SCC in BWR plant materials in terms of materials, environment, and stresses is shown.

working on identifying the factors involved in non-sensitized SCC and confirming the effectiveness of preventative maintenance techniques. The company has also been developing new materials that can inhibit SCC. This work has included developing techniques for evaluating the characteristics of SCC including the crack initiation life and crack growth rates (see Fig. 3).

Identification of Factors Behind SCC and Removal of Surface Cold Working

If the surface of stainless steel is machined, fine grains with a diameter of 0.5 μm or less form in the surface-most region due to recrystallization induced by the machining. A further cold-worked layer forms beneath this due to slip deformation, also caused by the machining. It has been identified that these microstructural changes play a significant role in non-sensitized SCC[(1), (2)].

Fig. 4 shows the relationship between SCC crack depth and surface hardness for a test piece subjected to SCC testing conducted in a simulated BWR water environment (uni-axial constant load tests)[(3)]. The graph shows how the SCC crack depth increases dramatically after machining of the surface increases the surface hardness beyond 300 HV (vickers hardness).

To eliminate this surface cold-worked layer as a cause of SCC, the flap wheel and CNS (clean 'n strip) polishing techniques have been used on the reactor shroud and other components for recent plants.

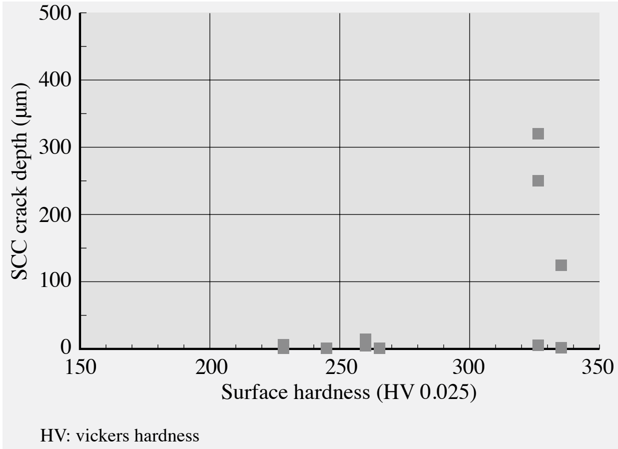

Fig. 4—Relationship between SCC Crack Depth and Surface Hardness.
The graph shows the relationship between SCC crack depth (obtained by cross-sectional observation) and surface hardness for a test piece subject to 10,000 hours of uni-axial constant load testing.

Fig. 5 shows the results of using EBSD (electron back scattering diffraction) to analyze the structure of SUS316L that has been subject to various types of surface finishing. After roughing (for the 300-HV and above materials in Fig. 4), finishing machining, and grinding, the materials were finished by using first flap wheel and then CNS polishing to remove the surface layer of machining.

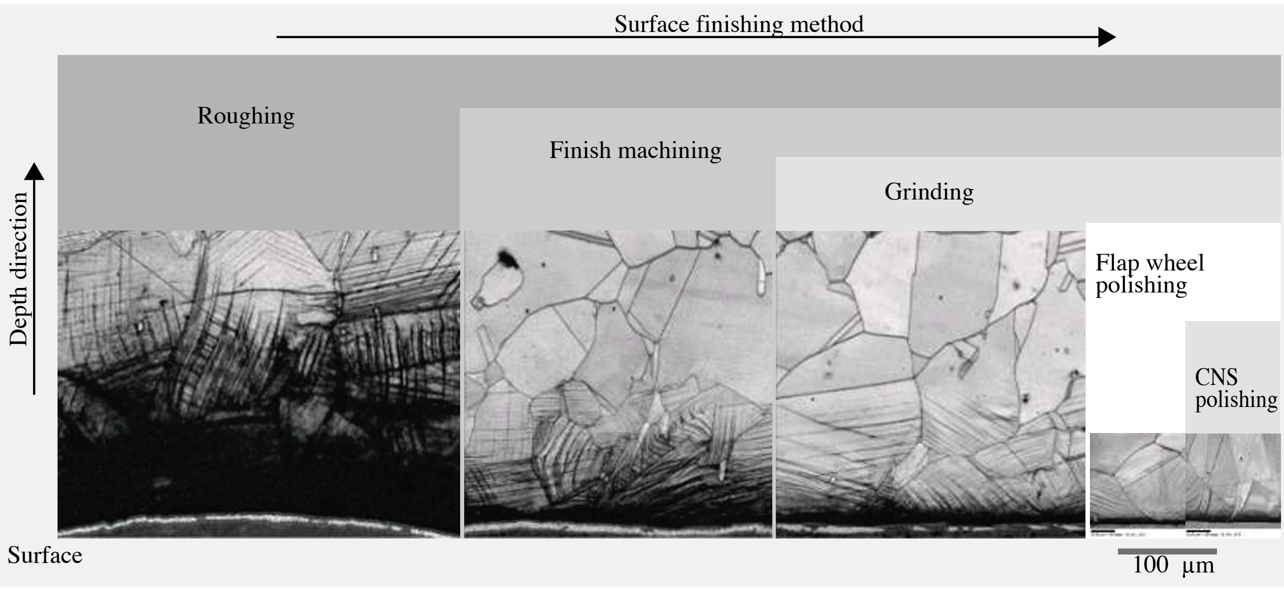

Fig. 5—Results of EBSD Analysis of SUS316L Surface Layer that has been Subjected to Various Surface Machining (Image Quality).
The figure shows the results of EBSD (electron back scattering diffraction) analysis of the cross-sectional structure of surface regions of material that has undergone various types of surface finishing. The black regions indicate the cold-worked layer. The material structures with a hardness of 300 HV or more shown previously in Fig. 4 correspond to the rough finished material in this figure.

As using flap wheel, CNS, or other polishing compresses the residual stresses in the surface, it can simultaneously address both material and stress-related factors.

Techniques for Evaluating SCC

Techniques for evaluating SCC are necessary to confirm the effectiveness of preventative maintenance techniques. Because improvements to SCC resistance make it essential that even a weak tendency for SCC to occur can be identified, Hitachi is working on evaluating the characteristics of SCC initiation through measures such as the long-duration (10,000 h) testing shown in Fig. 4.

To determine the integrity of equipment in which SCC has occurred, it is the role of private industry to produce reference SCC crack growth rate curves for stainless steel and nickel-based alloys, and the government's role to verify these. Obtaining highly reliable data requires that the number of repetitions be increased to confirm repeatability and Hitachi is working on extending its range of test equipment. Development of test pieces with constant stress intensity factor is also in progress to determine the influence of mechanical factors that affect SCC crack growth rate[(4), (5)].

Material Improvement (Grain-boundary-character-controlled Materials)

It is believed that grain boundary separation can progress easily at grain boundaries where the orientation of the adjacent crystals is not aligned (random grain boundaries).

Grain-boundary-character-controlled materials are materials in which the microstructure is controlled to increase the proportion of matched grain boundaries at which the adjacent crystals are oriented in a particular way. It is anticipated that this will improve SCC resistance by isolating regions of joined-up random grain boundaries.

Fig. 6 shows the results of a CBB (creviced bent beam) test using a notched test piece. The results show that, compared to the non-controlled material, the SCC crack length is much shorter for the controlled material. Also, for both materials, the number of cracks is much lower at matched grain boundaries and therefore the initiation and growth of SCC is inhibited in the grain-boundary-character-controlled material in which the proportion of matched grain boundaries has been increased.

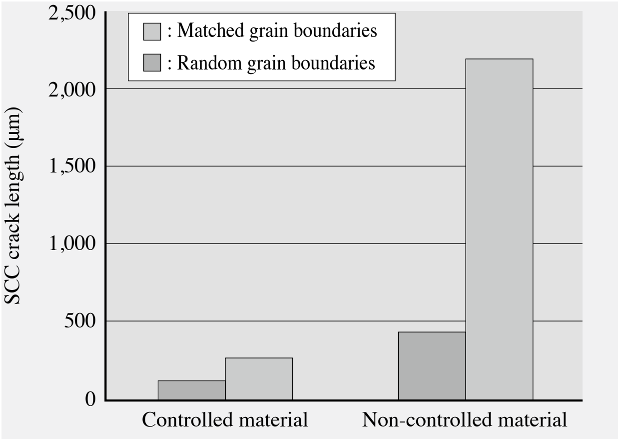

Fig. 6—Evaluation of SCC Resistance of Grain-boundary-character-controlled Material [CBB (creviced bent beam) test results].
The graph shows a comparison of SCC crack length in the notched region of grain-boundary-character-controlled and non-controlled SUS316L that had been immersed in 288-°C water for 2,000 h.

WELDING TECHNIQUES

Hitachi is working on the development of laser welding techniques with the aim of developing manufacturing techniques that offer high quality and high efficiency. Laser welding is also expected to have benefits for reducing welding deformation (plastic strain) and residual welding stresses, both factors that lead to SCC.

Laser-arc Hybrid Welding

Hitachi has developed a hybrid welding technique for stainless products that combines YAG (yttrium, aluminum, garnet) laser with TIG (tungsten inert gas) or MIG (metal inert gas) welding (see Fig. 7).

It has been confirmed that the new method significantly reduces welding deformation compared to the previous TIG welding method. The high

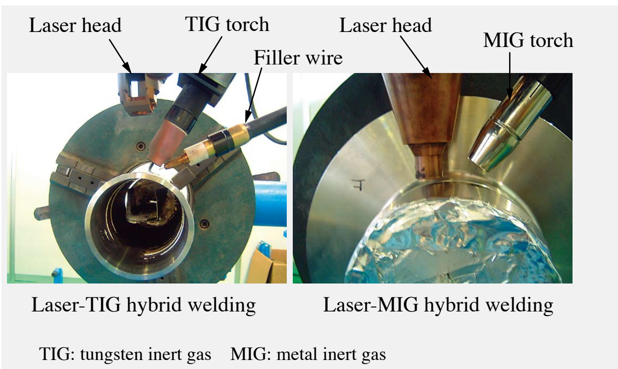

Fig. 7—Laser-arc Hybrid Welding.
The photographs show the layout around the welding head.

quality joints were confirmed and the products are currently being welded by the techniques.

High-energy Laser Welding

Hitachi has developed a welding technique that reduces residual welding stress through a narrower groove by using high-energy-density laser welding to weld heavy plate with a thickness of 25 mm or more (see Fig. 8).

It has been confirmed that this technique can be used with plate thicknesses of 50 mm or more and that it reduces the maximum value of residual stress and the range of tensile stresses compared to narrow-groove TIG welding.

It is expected that the technique reduces the plastic deformation of base metal near the weld subject to plastic strain making it effective for improving SCC performance.

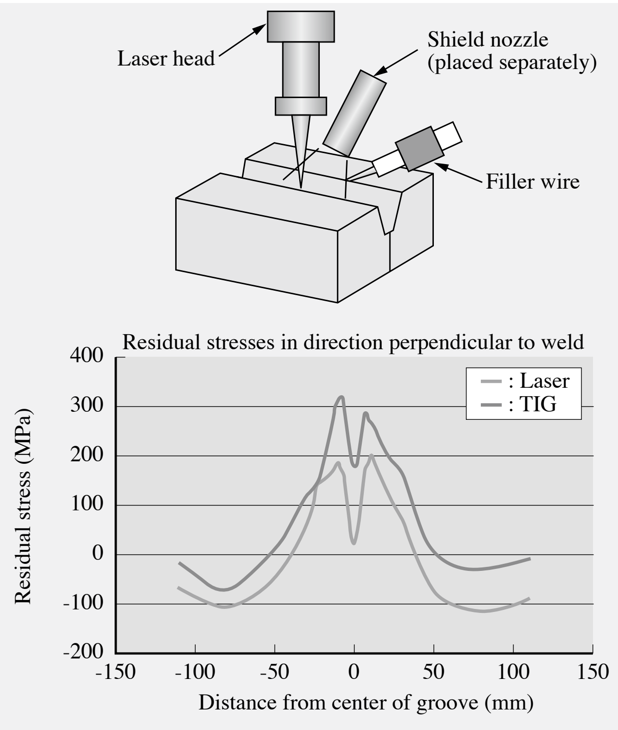

Fig. 8—Measurement of Residual Stress after Narrow-groove Laser Welding.
The graph shows the residual stresses in the direction perpendicular to the weld in the surfaces of narrow-groove laser welded and TIG welded joins in stainless steel (50-mm plate).

CONCLUSIONS

This article has described how the factors behind SCC are identified and improvements in materials made by describing the effects of the cold-worked layer and techniques for countering these effects, and the development of new materials. In the area of improvements to manufacturing processes, the article has also detailed progress in the development of laser welding.

Measures for dealing with SCC are an important issue for coping with aging plants and Hitachi has been working actively to identify the factors involved in non-sensitized SCC and confirm the effectiveness of countermeasures. The company is also developing new technologies such as grain-boundary-character-controlled materials and working on more advanced preventative maintenance techniques.

Hitachi-GE Nuclear Energy, Ltd. intends to continue undertaking joint research with GE-Hitachi Nuclear Energy Americas LLC into technical developments for making the materials used in BWR plants even more reliable.

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