Significance of Reheat Cracks to the Integrity of Pressure Vessels for Light-Water Reactors

Based on available metallurgical information microscopic grain boundary decohesions, which are not detectable by commercial NDT methods, are assumed to be not detrimental to the integrity of nuclear pressure vessels.

BY D. A. CANONICO

ABSTRACT. Reheat cracks usually manifest themselves as macroscopic defects that are detectable by the usual nondestructive testing (NDT) procedures or as microscopic grain boundary decohesions (GBD) that are beyond the limit of detection by commercial NDT procedures. This paper has concentrated on the significance of the microscopic cracks that may go undetected. The probability that GBD exist in the heat-affected zones (HAZ) of weldments of pressure vessel steels is high; particularly in SA 508 Class 2 weldments.

The GBD reside in the coarse-grained region of the HAZ. The microstructure of this region tends to be a tempered martensite or lower bainite, a structure whose fracture toughness is superior to that of higher temperature transformation products (upper bainite and pearlite-ferrite aggregate). Further, this region should be less sensitive to irradiation embrittlement. Toughness data for this region in either the unirradiated or irradiated condition are sparse; however, those data that are available indicate that this area is superior in toughness to the base metal.

A sample of the HAZ from the prolongation-weldment from the

Heavy Section Steel Technology program Intermediate Test Vessel (ITV) No. 4 was examined by the Staatliche Materialprüfungsanstalt (MPA). They reported GBD 5 mm (0.2 in.) long. This prompted an examination of the HAZ from the ITV vessel that had been tested to failure at 24 °C (75 F). During testing, the region of the weld which contained the flaw that initiated the failure was strained up to 0.5%. A metallographic examination of this region of the weldment revealed GBD, but none of the size reported by the MPA. Further, there was no evidence that the GBD had extended as a consequence of the tests. Fracture toughness values in excess of 220 MPa/m (200 ksi/in.) were obtained at -18 °C (0 F).

On the basis of the metallurgical information available for microstructures similar to those of the coarse-grained region of the HAZ as well as on the basis of experimental data (admittedly sparse), it can be assumed that the GBD that exist in these steels are not detrimental to the integrity of the nuclear pressure vessels. This position on the significance of reheat cracks is premised to a large extent on circumstantial evidence. Additional fracture toughness tests of actual weldments would lend considerable support to this conclusion.

Introduction

The pressure vessels used as the primary containment for light-water nuclear power plants are fabricated from thick-walled plate or forgings by welding. Figure 1 provides a schematic view indicating the various components that are joined together to produce a large pressure vessel. Figure 2 is a photograph of the Oyster Creek nuclear power plant being prepared for hydrostatic testing prior to shipment. Figure 1 depicts the procedure used when plate is employed. The individually formed plates (usually 3) are joined longitudinally by welding to provide a single course. If forgings are
used, a course is manufactured by ring rolling or press forging (over a mandrel) and a single ingot of steel. This procedure eliminates the need for longitudinal weld seams.

Welding is usually accomplished by either the submerged arc (SA) or shielded-metal arc (SMA) welding processes. The SA process is a high deposition rate process that can be automated. Prior to welding the base metals are prepared by machining a weld joint that is nondestructively examined to ensure its soundness. Welding is done with a multipass technique. Approximately 100 passes may be used to complete a weld between two thick [150 to 300 mm (6 to 12 in.)] plates or forgings.

The filler metal and fluxes are selected for their compatibility with the base metal. Frequently, the deposited weld metal is nearly identical to the pressure vessel steel except for its carbon content, which is usually considerably lower. This lower carbon content is reflected in the excellent toughness exhibited by the weld metals. Figure 3 illustrates the effect of carbon content on toughness.

The welding operation melts both the filler metal and the base metals being joined, and the deposited weld has a chemical composition that is a result of this mixture. The amount of mixing or dilution that occurs is a function of the welding procedure and joint design, and will vary throughout the weld. The area in the base metal immediately adjacent to the weld deposit undergoes a thermal excursion up to its melting point.[approximately 1593 C (2900 F)]. This region which is metallurgically affected by the welding process is referred to as the heat-affected zone (HAZ). The base metal is heated to maximum temperatures that range from that of the preheat temperature [approximately 149-260 C (300-500 F)] to the melting point of the steel.

A schematic representation of the influence of the thermal excursion on the microstructure of the base metal is provided in Fig. 4. Over a short distance the base metal is heated to just below the melting point and that which did not melt. This region has been heated to just below the melting point of the steel. During welding this region has been transformed to austenite, and the austenite grains have grown to rather large sizes. An example of a coarse-grained austenitic microstructure that can exist in this region of the HAZ is shown in Fig. 5.

Attention has been directed to this region of a weldment in recent years due to the detection of cracks in the boundaries between these coarse grains. The first instance, and the one which received the most attention, was related to the presence of cracks in the base metal HAZ beneath the stainless steel overlay that protects against corrosion in pressure vessels for light water nuclear reactors. These cracks were found after postweld heat treatment and were attributed to a number of factors including:

1. The composition of the base metal (SA 508 Class 2 is much more susceptible than SA 533 Grade B Class 1).
2. The overlay (i.e., surfacing) welding procedure (high heat-input single-pass welds are more susceptible than low heat-input multipass welds).
3. The liquation of low melting point constituents (these serve as stress intensifiers during the stress-relief treatment).

The sensitivity of these underclad regions to cracking has been referred to as creep embrittlement or stress-relief cracking. This aspect of reheat cracking has received a good deal of attention. Investigations by commercial organizations in the United States and abroad assessed the significance of these underclad cracks. Lorenz and Luginbühl concluded that increased susceptibility was noted in those steels that contained higher quantities of such elements as chromium, molybdenum and vanadium and indicated that the cracking could be minimized (and possibly eliminated) with improved cladding procedures. H. Nakamura established an equation, based on extensive tests with low-alloy high-strength structural steels, that predicts crack sensitivity based on the main alloying elements:
Fig. 3—Effect of carbon content on the shape of the Charpy V-notch transition temperature curve for steel. Values on curves are carbon content in wt-%

Fig. 4—Relation between the peak temperatures experienced by various regions in a weld, and how these correlate with the iron-carbon phase diagram

$$\Delta G = \%Cr + 3.3 \times [\% Mo] + 8.1 \times [\% V] - 2 \quad (1)$$

A positive $\Delta G$ value indicates that a steel is sensitive to reheat cracking. Ayres et al. did an extensive assessment of the significance of the underclad cracks on the integrity of thick-walled pressure vessels; they concluded that the underclad cracks have no detrimental effect on these vessels under all operating conditions anticipated during the design life of the pressure vessel.

Finally, the most comprehensive report concerning the status of the underclad cracks was prepared by Vinciber and Pense for the Pressure Vessel Research Committee of the Welding Research Council. The conclusions of these investigations were:

1. Underclad cracks did occur.
2. Their presence could be minimized.
3. They were of no significance in regard to the integrity of the pressure vessels in which they were found.

About the same time that the underclad cracks were brought to the attention of the technical community, the presence of reheat cracks in butt welds was reported. This phenomenon was introduced by Professor Karl Kussmaul at the Sixth Annual Heavy Section Steel Technology (HSST) Information meeting in 1972. These cracks manifest themselves in the coarse-grained region of the HAZ of the longitudinal and circumferential welds in reactor pressure vessels. Professor Kussmaul reported the presence of such cracks in a German forging grade steel designated 22NiMoCr37. This paper will consider the significance of reheat cracks in butt welds on the integrity of pressure vessels for light water reactors.
Investigations of Reheat Cracks

Reheat cracks can manifest themselves as microscopic grain boundary decohesions (Fig. 6) and as large macrocracks. An example of an extremely large stress-relief crack is represented by the defect responsible for the failure of the Cocken­zie Vessel in England during proof testing. The flaw was approximately 33.0 cm (13 in.) long and 9 cm (3½ in.) deep in a pressure vessel whose wall was 14 cm (5¾ in.) thick.

The most extensive examination of commercial weldments has been undertaken by the Staatliche Materialprüfungsanstalt (MPA) at the University of Stuttgart in the Federal Republic of Germany. This work has been reported at various meetings and in numerous publications by Prof. Kuss­maul and his colleagues. The MPA has conducted extensive met­allographic studies of the HAZ of commercial weldments of various grades of steel. Many of the steels investigated by the MPA are not applicable to this paper because they are not employed for Class 1 nuclear pressure vessels. Of all the steels investigated by the MPA, only the 22NiMoCr37 and the 20MnMoNi55 steels are similar to the pressure vessel steels employed in the fabrication of nuclear pressure vessels in the United States. The two German grades are nearly identical to SA 508 Class 2 and SA 533 Grade B Class 1, respectively.

The chemical compositional limits for these steels are provided in Table 1. The SA 508 Class 2 steel is considerably more sensitive to reheat cracking than the SA 533 Grade B. This difference in sensitivity was particularly noted in the underclad crack studies. These observations substantiate the prediction of sensitivity based on the Nakamura equation—equation (1). Applying this equation to nominal compositions for SA 533 Grade B steel (0.22% C, 1.35% Mn, 0.55% Mo, 0.60% Ni) and SA 508 Class 2 steel (0.22% C, 0.75% Mn, 0.35% Cr, 0.65% Mo, 0.70% Ni and 0.03% V) provides AG values of -0.19 and +0.74 respectively. The MPA studies have concentrated on the 22NiMoCr37 forging steel (similar to SA 508 Class 2) because of its higher susceptibility to reheat cracking.

The MPA has shown through an extensive met­allographic examination of the HAZ of welds that reheat cracks do exist. They attribute the cracks to the resolution of the metallic (chromium, molybdenum, vanadium) carbides as a consequence of the exposure of the base metal adjacent to the fusion line to temperatures near the melting point of the steel. Vinckier described the mechanism for stress relief cracking as follows:

Although the mechanism of stress relief cracking is not completely understood, it is now generally ac­cepted that cracks form as a result of relaxation strains exceeding the ductility of the HAZ or weld metal. According to the existing theories of reheat cracking, carbides (vanadium, molybdenum, chromium, etc.) are taken into solution in the HAZ when its temperature exceeds 1200°C (2129°F). These elements reprecipitate as carbides in the lattice structure during reheating and stiffen the grain interiors. The plastic creep strains concentrate at the grain boundaries, and the grain boundary sliding leads to wedge and cavitation cracking.

In 1972 when Prof. Kussmaul re­ported the detection of reheat cracks in steels similar to those employed in the United States for the fabrication of nuclear pressure vessels, the HSST program undertook an examination of the HAZ of welds. The samples selected were SA welds between plates of A 533 Grade B Class 1 steel. Samples were obtained parallel to the direction of welding. The specimens which measured 2.5 by 7.5 cm (1.0 by 3.0 in.) were progressively polished from the base metal toward the weld metal.

Figures 7 consists of two montages made of the HAZ in which there was no evidence of reheat cracking. (Figure 5 contains photomicrographs taken during this examination.) The method of sectioning the weld is shown in the sketch in the upper right-hand corner of Fig. 7. A number of areas were examined, but no evidence of GBD was found.

In September 1974 it was reported to the HSST program office that the MPA had examined a sample of the weldment from the prolongation on Intermediate Test Vessel (ITV) No. 4 and found “the worst case of microcracking that they had observed to date.” The ITV-4 tests are described by R. H. Bryan et al. The longest cracks were approximately 5 mm (0.2 in.) long. Further, incidence of occurrence was high. This prompted an examination of the HAZ of ITV-4.

### Table 1—Comparison Between the Chemical Compositions of German and United States Steels

<table>
<thead>
<tr>
<th>Steel identification</th>
<th>Carbon</th>
<th>Manganese</th>
<th>Phosphorus</th>
<th>Sulfur</th>
<th>Silicon</th>
<th>Nickel</th>
<th>Chromium</th>
<th>Molybdenum</th>
<th>Vanadium</th>
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<tr>
<td>SA 508 Class 2</td>
<td>0.27</td>
<td>0.05</td>
<td>0.025</td>
<td>0.025</td>
<td>0.15</td>
<td>0.50</td>
<td>0.25</td>
<td>0.55</td>
<td>0.05</td>
</tr>
<tr>
<td>22NiMoCr37</td>
<td>0.17</td>
<td>0.50</td>
<td>&lt;0.025</td>
<td>&lt;0.025</td>
<td>≤0.35</td>
<td>1.00</td>
<td>0.50</td>
<td>0.60</td>
<td>≤0.05</td>
</tr>
<tr>
<td>SA 533 Grade B</td>
<td>0.25</td>
<td>1.10</td>
<td>0.030</td>
<td>0.040</td>
<td>0.13</td>
<td>0.37</td>
<td>0.50</td>
<td>0.60</td>
<td>0.41</td>
</tr>
<tr>
<td>SA 508 Class 3</td>
<td>0.15</td>
<td>0.20</td>
<td>0.025</td>
<td>0.025</td>
<td>0.15</td>
<td>0.40</td>
<td>0.45</td>
<td>0.64</td>
<td>≤0.05</td>
</tr>
<tr>
<td>20MnMoNi55</td>
<td>0.25</td>
<td>1.50</td>
<td>&lt;0.025</td>
<td>&lt;0.025</td>
<td>0.15</td>
<td>0.80</td>
<td>0.60</td>
<td>0.45</td>
<td>0.60</td>
</tr>
</tbody>
</table>

*Single number indicates a maximum value; double numbers denote range.*
Fig. 7—Example of the sectioning procedure used in the investigation of a submerged-arc weldment between two A 533 Grade B Class 1 plates. The photomacrograph in the upper right-hand corner shows the surface being examined during one of the intermediate stages of polishing. The vertical and horizontal montages show typical microstructures observed during the metallographic examination. No reheat cracks were observed in this specimen.
It was learned that MPA had found the cracks near the root location in the weldment. This is the root region of the double-J weld joint design used in welding ITV-4. To facilitate the examination of ITV-4, precracked Charpy (PCC) archive samples of tests conducted on the weld metal at the same location in the ITV-4 prolongation were selected. The PCC sample had been tested at 93°C (200°F) and exhibited a shear failure as a consequence of being tested at this temperature. The specimen exhibited a weld metal toughness of 193 MPa (176 ksi) at the test temperature.

The first indications of grain boundary decohesions were those shown in Fig. 8. The two GBD appeared to be "filled" even at magnifications of \( \times 1000 \). A scanning-electron microscopy (SEM) study at \( \times 3000 \) confirmed that these were GBD. The metallographic examination was continued and additional GBD were observed. These latter GBD were more easily resolved. Etching appears to emphasize the presence of cracks—Fig. 9.

In addition to the metallographic examination of archive PCC specimens from the ITV-4 prolongation, researchers visited the MPA. Portions of the summary of the trip report, that are pertinent to the MPA visit are as follows:

"The Staatliche Materialprüfungsanstalt (MPA) has metallographically characterized the heat-affected zone (HAZ) of 80 production qualification weldments of 22NiMoCr37 steel (German designation for a steel similar in composition to ASTM A 508 Class 2). These weldments covered a broad spectrum of welding processes and procedures. Approximately 20 of these welds contained cracks up to 0.50 mm long.

"The intent of the MPA program is to establish qualification standards, which the German Reactor Safety Board will impose on nuclear pressure vessel fabricators. These standards will include extensive metallographic examinations of the qualification weldments. These destructive examinations will be in addition to the usual nondestructive and mechanical property tests currently imposed on the fabricators.

"The results from the MPA examination of the production qualification weldments is not cause for alarm. The cracks (about 0.5 mm in length) in themselves are not significant. Currently, there is no basis for suggesting a reduction in the service life of any unit (nor do I personally foresee such a conclusion).

"The MPA is reducing its efforts in metallographic examination and is emphasizing the characterization of the mechanical properties of the weldment HAZ through the use of simulated thermal cycles imposed on base metal materials. Specimen blanks are heated to 1300°F and quenched to simulate the HAZ near the fusion line in a heavy section weldment. The specimens are subsequently exposed to elevated temperatures (usually 610°C) under loads designed to provide various levels of creep in a constant period of time. This thermal-mechanical treatment is intended to simulate a stress-relief treatment on the coarse-grained HAZ. The specimens are then tensile tested at 320°C to determine the influence of the thermal-mechanical treatment on the properties of these regions.

"In addition to this work, the MPA has proposed a $1.2 million research program aimed at perfecting the application of current state-of-the-art nondestructive examination techniques to assure that insignificant discontinuities in the region of HAZ are not masking larger cracks.

"The MPA studies are primarily on forging materials. However, some work has been done on plates, and no sensitivity toward cracking has been found for ASTM A 533 Grade B Class 1 steel. This resistance to cracking exhibited by the ASTM A 533 Grade B Class 1 steel was also true in the extensive underclad cracking study conducted under the auspices of the Pressure Vessel Research Committee.

"The quality of the studies under way at the MPA is excellent. It has an exceptionally well-equipped facility staffed by qualified personnel. Its goal, to assure the integrity of the nuclear pressure vessel over its entire lifetime, is commendable. I would recommend that the U.S.A. cooperate with the German researchers in this effort. Although not a novel observation, MPA did find a high incidence of cracking in the HAZ of the production weldments. These small cracks are not significant unless they serve as the cause of an accelerated damage mechanism. For example it is possible that the subcritical crack growth rate, \( \Delta K \), could be more rapid in this region for a given stress intensity variation, \( \Delta K \), due to the link-up of the
individual small cracks. Also the absence of cracks in the HAZ does not assure a tough weldment. It is possible that an excessively coarse-grained HAZ is a region of inferior toughness.

"It would be beneficial for the U.S.A. to embark on a similar examination of welds produced in our country. The goal of this study should be to establish the character of the HAZ; we must determine the toughness of the weldment under conditions of service that can affect material properties.

"On November 14, 1974, a meeting was held between representatives of Westinghouse Electric Company, MPA, and ORNL (represented by Professor A. W. Pense, Consultant, and myself) to discuss the results of a metallographic examination of an ASTM A 508 Class 2 weldment provided MPA by Westinghouse Research Laboratories—Europe (WRL-E). The weldment is from the prolongation from Heavy Section Steel Technology (HSST) program Intermediate Test Vessel 4 (ITV-4). The MPA found extensive cracking in the root region of the sample. The cracks were up to 5 mm long, 10 times larger than any that MPA had previously seen in its examination of production qualification weldments. The cracks were in the HAZ (adjacent to the fusion line) in regions where the grain size was near ASTM No. 1. This grain size, although extremely coarse, is within the range of sizes observed by MPA (but near the lower 15% of the spectrum). Previously WRL-E had examined the upper portion of one half of the weldment (it was sectioned longitudinally through the weld) and had not found any indications; this was true even after WRL-E had bent the polished specimens and reexamined them for cracks. When WRL-E investigators learned of the results of the MPA examination, they examined specimens from near the root region of their half of the weld and found hot cracks up to 4 mm long. When ORNL learned of these results we examined broken Charpy V-notch specimens from the root of ITV-4 and found a few grain boundary decohesions (we required 100 to 1000X magnification to ascertain that they were indeed cracks).

"The MPA observed that the chemical analysis of the ASTM A 508 Class 2 forging steel is such that this steel is more sensitive to stress-relief cracking than the similar German grade. Further, the heat of steel used in the fabrication of ITV-4 is near the upper limit of the allowable chemical composition limits in the ASTM specification. This specimen exhibited the worst cracks that MPA had observed to date. It must be emphasized that the sample was from the ITV-4 prolongation. If indeed the sample does represent the ITV-4 vessel, then we can unequivocally state that it withstood a stress nearly 3 times the design stress at 75°F. This fact does imply that a significant toughness exists in this region."

The ITV-4 was tested at 24 C (75 F), and the vessel underwent a strain of 0.17% at the outside surface 180 deg away from the flaw during testing. In the vicinity of the flaw, the weld metal underwent a strain of 0.5% in the circumferential direction. Failure occurred when the internal pressure of the vessel reached 187.7 MPa (26,500 psi), a value approximately 3 times higher than that allowed by the design rules of Section III of the ASME Code.

The vessel contained two fatigue-sharpened flaws, each approximately 21 cm long and 7.5 cm deep (8.25 in. and 3.0 in.). Failure initiated at the flaw located in the weld metal. The crack propagated in the weld metal and terminated in the lower head and at the bolt holes in the upper region. There was no evidence that the crack ran out of the weld metal into the HAZ.

The ITV-4 vessel presented an excellent opportunity to investigate a weldment that not only indicated a suscep-
Fig. 10—View of fracture surface from intermediate test vessel no. 4. The lines identify the cutting plan. The letters and numbers are the code used to identify the various regions of the fracture surface. (B-2 = 21.59 cm; B-3 = 21.27 cm; B-4 = 22.54 cm; B = 35.56 cm; B-5 = 20.64 cm; B-6 = 21.59 cm; B-7 = 21.39 cm. Total length = 166.37 cm)

Fig. 11—Transverse section of an area of the weld from intermediate test vessel no. 4. Each weld pass is evident in this photomacrograph. Note the irregularity of the fusion line and, therefore, the coarse-grained region of the heat-affected zone. This irregularity is the reason it is so difficult to test this region.

Fig. 12—Various types of defects found in the heat-affected zone of intermediate test vessel no. 4. The photomicrographs (left to right) show incipient melting, lack of fusion, and reheat cracking, respectively.
region of the HAZ where the austenite grain size was much larger than that in other regions.

The ORNL examination centered about the ¾ depth location, the location where the MPA observed the large reheat cracks in their examination of the prolongation from ITV-4. No large cracks were seen. Figure 13 is typical of the structure that was observed in the examination of the HAZ from ITV-4. In summary, the ORNL investigation of the HAZ from ITV-4 did not reveal any large microcracks nor any evidence that the GBD had extended as a consequence of the test. During testing, the outer surface of the weld was in excess of the yield strength of the base metal as evidenced by 0.5% strain recorded; yet there was no apparent damage to the HAZ.

A fracture toughness study of the HAZ was conducted from the longitudinal weld in ITV-4. An electron beam (EB) weld crack initiation technique was used to place a sharp crack in the exact location desired. The accuracy with which an EB weld can be placed in the exact location desired is quite good. Tests to date, admittedly limited, have shown that the fracture toughness of the region of interest is estimated to be at least equal to that of the base metal. Further, the $K_{IC}$ values calculated, based on the equivalent energy method, from precracked Charpy specimens are about 220 MPa $\sqrt{m}$ (200 ksi $\sqrt{in}$).

In their efforts to study the properties of the HAZ of pressure vessel steels, the MPA developed methods for simulating the microstructure of the base metal immediately adjacent to the fusion line. They did this by rapidly heating bars of steel machined from the alloys of interest (for example, 22NiMoCr37) to 1300 C (2372 F) and quenching them. These coarse-grained specimens could be given a simulated postweld heat treatment (PWHT) under stress to determine the effect of time and temperature on the creep-strain tolerance of this microstructure. They found that the 22NiMoCr37 alloy underwent a severe loss of Charpy V-notch ($C_{V}$) toughness at 320 C (608 F) when a specimen subjected to the 1300 C (2372 F) simulated HAZ thermal excursion was PWHT at 610 C (1130 F) for 6 hours (h) under a load of 180 MPa (26 ksi). It should be noted that the 180 MPa stress value at 160 C (320 F) is near (if not above) the ultimate tensile strength of the conventionally heat-treated (quenched and tempered) thick-walled pressure vessel steels used in the fabrication of reactor pressure vessels.

The MPA has shown that reactor pressure vessel steels, in particular 22NiMoCr37 and SA 508 Class 2 are susceptible to creep embrittlement if the material is heated to 1300 C (2372 F), quenched in water, and aged at 610 C (1130 F) for 6 h under a load of 180 MPa (26 ksi). Their tests also show that the strength of the steel in the as-quenched and aged condition has an ultimate and yield strength of 880 MPa and 790 MPa (127 ksi and 114 ksi), respectively. This level of yield strength is over twice that of the minimum room-temperature value required by the specification for SA 508 Class 2 (345 MPa (50 ksi)).

These microcracks may exist in the HAZ of reactor pressure vessel weldments is an accepted fact. Their presence has been reported by a number of research and production organizations throughout the world. The assessment of the significance of these microcracks and of the microstructure in which they reside on the structural integrity of the thick-walled nuclear pressure vessels used in the U.S. must include consideration of a number of other factors, including the materials themselves, welding procedures, microstructural effects, sensitivity to radiation damage, and ultimately the toughness of the coarse-grained region of the HAZ in which the reheat cracks reside.

**Material Considerations**

The pressure vessels used for the primary containment of the light-water nuclear power plants in the United States are fabricated from essentially two base metal compositions. These are steels identified as SA 333 Grade B Class 1 and SA 508 Class 2.

The pressure vessels used for the primary containment of the light-water nuclear power plants in the United States are fabricated from essentially two base metal compositions. These are steels identified as SA 333 Grade B Class 1 and SA 508 Class 2. The SA before the specification number indicates that the material has been accepted for use by the ASME Code. Further, both steels are approved by Sect. III, Division 1, Nuclear Power Plant Component, of the ASME Code for the construction of Class 1 pressure-containing components for nuclear applications.

For these applications there are certain requirements that the steels must meet in addition to those of the SA specification. For the most part these additional requirements assure that minimum levels of toughness are met by the heats of steel that are used. These criteria are set in Paragraph NB2331 of Section III, Division 1, which requires that Charpy V-notch ($C_{V}$) specimens representative of the pressure-vessel steels be able to absorb 60 J (50 ft-lb) and 0.890 mm (35 mils) lateral expansion at a temperature 33 K (60 F) above its nil ductility temperature (NDT) as determined by the drop-weight test.

The criteria of 60 J and 0.890 mm must be met in order to determine the NDT reference temperature (RT$_{NDT}$). The RT$_{NDT}$ is required to establish the critical stress intensity factor ($K_{IC}$) curve that assures that the arrest criterion for avoiding significant fracture can be determined for the material being evaluated. The $K_{IC}$ curve and its relationship to the integrity of reactor pressure vessels is discussed in Appendix G of Sect. III, Division 1 (ref. 20) and in Welding Research Council Bulletin No. 175 (ref. 21).

If the 60 J, 0.890 mm criteria are not met at NDT + 33 K, then $C_{V}$ testing is done at increasingly higher temperatures until these values are achieved. The RT$_{NDT}$ is then adjusted upward to a temperature 33 K (60 F) below that at which these criteria are met. Further, those heats of steel that are used in the section of the pressure vessel that surrounds the core must exhibit the ability to absorb at least 102 J (75 ft-lb) on the upper shelf of the $C_{V}$ energy vs. temperature curve.

In summary, a steel that is employed in the fabrication of a nuclear pressure vessel...
vessel must satisfy the requirements of the SA specification, which dictates the limits on chemical composition, permissible melting and processing practices, and minimum mechanical properties as well as other criteria that are established by the ASME Code, the Federal Register, and Nuclear Regulatory Commission regulatory guides. These criteria provide the assurance that the steels possess fracture toughness properties that should prevent a catastrophic failure when the steels are put into service. The chemical compositions of the two steels are controlled by their specifications. Hence, their sensitivity toward reheat cracking can be easily evaluated.

Metallurgical Considerations

The HAZ of a weldment (Fig. 4) consists of a number of different microstructures across its short distance. The HAZ in weldments of thick sections of high-alloy steels will transform upon cooling in accordance with their hardenability. The metallurgical response of a steel is usually described through the use of time-temperature-transformation (TTT) diagrams. A TTT diagram representative of SA 533 Grade B steel is shown in Fig. 14. This steel has a strong tendency to transform to bainite [see A + F + C area, ~510 °C (950 F), of Fig. 14]. The rapid quenching that the HAZ undergoes will shift the transformation to longer times. The TTT diagram in Fig. 14 depicts equilibrium conditions. A continuous cooling transformation (CT) diagram depicts the effects of commercial quenching operations.

When compared to a TTT diagram for the same heat of steel, the CT diagram is transposed to longer times and lower temperatures. Further, a coarse austenite grain size tends to shift the transformation behavior to longer times, thereby enhancing the possibility of obtaining a lower transformation product during quenching. Combinations of these metallurgical factors—large austenite grain size, continuous cooling, and large heat...
sink—promote the transformation of a steel to martensite. Untempered martensite has poor toughness properties, but martensite that is correctly tempered has superior properties.

Figure 15 shows an example of the influence of the microstructure on the C_T toughness of low-alloy high-strength steel. (Figure 15 does not represent the microstructure in SA 533 Grade B or SA 508 Class 2 steel; it is used only to illustrate the influence of microstructure on toughness.) It is evident that the structure with the best toughness is martensite. The martensite plus bainite structure is less tough but still quite acceptable.

Because of its rapid cooling rate, the microstructure of the coarse-grained region of the HAZ will contain the lowest transformation product possible for the SA 508 Class 2 and SA 533 Grade B Class 1 steels. Therefore, if correctly tempered, the coarse-grained region of the HAZ can indeed be superior to the remainder of the structure. If incorrectly tempered, it will have the poorest toughness of the entire structure. The correct tempering temperature for these steels ranges from about 621 to 677°C (about 1150 to 1250°F).

Design Considerations

It has been shown that the SA 508 Class 2 forging grade of steel is considerably more susceptible to reheat cracking than the SA 533 Grade B analysis (maximum ΔG, based on upper bound limits of chromium, molybdenum and vanadium, is +1.07 and +0.11, respectively, for the two steels). The maximum Nakamura number for the 22NiMoCr37 alloy is +1.55.

The high sensitivity of the SA 508 Class 2 steel is offset because longitudinal weld seams are not used when forgings are used in the fabrication of a nuclear pressure vessel. This design fact eliminates the possibility of stressing the HAZ of SA 508 Class 2 in the hoop direction.

Circumferential-weld seams are the only weld joint design used, and they are loaded in the axial direction. Further, the use of forgings removes or eliminates the longitudinal weld in the core region of the reactor. This, in turn, removes the SA 508 Class 2 weld from the high-flux region in the nuclear pressure vessel.

Material Properties

The HAZ of welds generally possesses superior tensile and toughness properties when compared to their chemically equivalent base metal. This is particularly true for low-alloy high-strength steels that are correctly post-weld heat treated.

A hardness traverse across a SA weldment made between two 30.5 cm thick (12 in.) plates of SA 533 Grade B Class 1 steel shows that the highest hardness found in the HAZ, Fig. 16. A fracture toughness study was conducted by Westinghouse Electric Corporation on SA weldments similar to that shown in Fig. 16. A C_T test of the HAZ of a 30 cm (11% in.) A 533 Grade B Class 1 steel specimen showed the 40 J (30 ft-lb) transition temperature (TT) to be -40°C (-40°F) or lower. This result can be compared to 40 J TT of -9°C (+15°F) and -12°C (+10°F), respectively, for 20.3 and 30.5 cm thick (8 and 12 in.) A 533 Grade B Class 1 base metals tested in the same study.

The fracture toughness of the HAZ of the 30 cm (11% in.) thick A 533 Grade B steel was measured using a WOL specimen. In accordance with the criteria of ASTM Specification E-399, a valid K_T value of 78.2 MPA√m (71.2 ksi√in.) was obtained with a 2T specimen at -328°C (-200°F). An invalid K_T value of 108 MPA√m (97.9 ksi√in.) was obtained at -101°C (-150°F). This latter test was also done with a 2TWOL specimen.

More recently, Grotske et al. have simulated the HAZ microstructure of SA 508 Class 2 steel weldments using thermal cycles representative of commercial practice [about 3780 kJ/m (96 kJ/in.)]. They found that specimens heated to 1343°C (2450°F) and not tempered (postweld heat treated) had room temperature C_T energy values less than that of the quenched and tempered base metal. However, in all tests in which the specimens were given a multicycle thermal excursion representative of a multipass welding procedure, the C_T toughness of the HAZ microstructure was superior to that of the base metal.

The specimen blanks obtained from the weld thermal-cycle simulations were also used for precracked Charpy tests. These specimens were used to obtain dynamic fracture toughness data for the simulated HAZ microstructure. Room-temperature dynamic-fracture toughness of specimens heated only to the peak temperature, 1343°C (2449°F), was about 30% lower than that of the base metal. When the specimens were subjected to a thermal excursion simulating that of a multipass welding procedure, the HAZ toughness was superior to that of the base metal.

Westinghouse Electric also conducted crack growth rate (da/dN) studies on a A 533 Grade B Class 1 base metal and HAZ. They found that at low ΔK (stress intensity range) levels the crack growth rate in the HAZ was lower than that of the base metal of commercial practice [about 3780 kJ/m (96 kJ/in.)]. They found that specimens heated to 1343°C (2450°F) and not tempered (postweld heat treated) had room temperature C_T energy values less than that of the quenched and tempered base metal. However, in all tests in which the specimens were given a multicycle thermal excursion representative of a multipass welding procedure, the C_T toughness of the HAZ microstructure was superior to that of the base metal.

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Westinghouse Electric also conducted crack growth rate (da/dN) studies on a A 533 Grade B Class 1 base metal and HAZ. They found that at low ΔK (stress intensity range) levels the crack growth rate in the HAZ was lower than that of the base metal or
weld metal and at high ΔK levels the crack growth rate was higher. At a ΔK value of 88 MPa√m (80 ksi√in) the crack growth rate is 0.002 mm (80 micro inches) per cycle for the HAZ vs. 0.00152 mm (60 micro inches) for the base metal at the 1/4 thickness location. These subcritical crack-growth data suggest that the HAZ may be more sensitive to stress-intensity levels than the base metal.

The Kernforschungsanlage Jülich GmbH prepared an SA weld between two pieces of A 533 Grade B Class 1 steel supplied by the HSST program office. They investigated the CV properties of the HAZ and weld metal. Their results indicated that the HAZ toughness was similar to that of the weld metal (and superior to that of the base metal).

Recently, the Electric Power Research Institute has sponsored an investigation of the fracture toughness of ferritic materials for nuclear pressure vessels. The study included the HAZ of structural weldments. The Combustion Engineering, Babcock and Wilcox, and Effects Technology corporations were involved in the study. Combustion Engineering conducted fracture toughness tests of the HAZ of welds made between thick plates of SA 533 Grade B Class 1 steel. They conducted drop-weight, CV, and fracture toughness (Kr) tests. The HAZ of both SA and SMA welds had lower drop-weight NDT than the base metal. The RTK for the HAZ was -40°C (-40°F) vs. a low value of -12°C (+10°F) and a high value of 16°C (60°F) for the base metals. The base metal study was of five heats of SA 533 Grade B Class 1. The HAZ CV toughness was also superior to that of the base metal.

In that same study researchers also determined a Kr curve for their data based on the rules in Appendix G of Section III of the ASME Code. The Kr curve for the HAZ was to the left (lower temperatures) of the base metal Kr curve. (The location of the Kr curve in a toughness vs. temperature plot is dictated by the RTK.) The fracture toughness data that Combustion Engineering obtained for the SA and SMA welds included 1T compact tension specimens. These results were plotted on the same figures that contained the Kr curve for the HAZ and in all cases the toughness values determined experimentally were superior to those predicted.

The investigation of welds was a major task of researchers in the Babcock and Wilcox study, who characterized 5 submerged-arc (SA) and 5 shielded-metal arc welds. All of the welds were made in thick [330-356 mm (13.14 in.)] SA 508 Class 2 steel forgings. The SA welds were made with a heat input of from 2835 to 4020 kJ/m (72 to 102 kJ/in.). The SMA welds were made using considerably lower heat inputs, 551-2205 kJ/m (14-56 kJ/in.).

In the SA weld study the toughness of the HAZ was in all cases superior or equal to that of the weld metal. The 68 J (50 ft-lb) temperature of the HAZ ranged from -34 to -79°C (-30 to -110°F) and from -4 to -62°C (+25 to -80°F) for the weld metal. The SMA weldments exhibited similar results. Comparative information was obtained for four SMA welds, and in three of them the HAZ was tougher than the weld metal.

MPA investigators have been involved in the testing of simulated HAZ from various heats of 22NiMoCr37. They have only reported a limited amount of work on the HAZ of weldments of this class of steel. In a CV study of an SA weld, the MPA reported a large spread in toughness values of the HAZ over the entire range of operat6ions investigated. The upper shelf CV toughness of the HAZ ranged from about 80 J (60 ft-lb) to about 200 J (148 ft-lb). The CV toughness limits of the HAZ were lower and higher than those of the base metal or weld metal. This study covered the entire HAZ, and it was not established which region of the HAZ was represented by the high or low values.

The lower bound limit of the CV toughness, 80 J (60 ft-lb) can be correlated to a Kt value through the relation proposed by Rolfe and Novak:

\[
\left( \frac{K_{t}}{\sigma_{f}} \right) = 5 \left( \frac{C_{V}}{\sigma_{f}} - 0.05 \right) \]  

(2)

where σf = 0.2% offset yield strength in ksi; C = Charpy V-notch upper shelf energy in ft-lb.

In making the calculation it was assumed that the lowest toughness was obtained in the region that would exhibit the highest yield strength. A yield strength of 689.5 MPa (100 ksi) was assumed to be representative of the strength of the coarse-grained regions in which the GBD occur. Based on an 80 joule toughness and a 689.5 MPa (100 ksi) yield strength, the calculated Kt of the HAZ is about 181 MPa√m (165 ksi√in).

The problem of placing the crack in the desired location in the HAZ has perplexed experimenters for some time. These difficulties have been recognized in Europe and in the USA. A technique employing the electron-beam (EB) welding procedure followed by hydrogen charging was developed at ORNL for placing a crack in precisely the desired location. This procedure was used to place cracks in the HAZ adjacent to the fusion line in an SA weldment between two plates of A 533 Grade B Class 1 steel. After the HAZ was cracked, Charpy-size specimens with an axial orientation perpendicular to the cracks were machined. These precracked Charpy (PC) specimens were tested under static load conditions, and their fracture toughness was calculated in accordance with the equivalent energy techniques.

The results of the tests on EB-cracked HAZ specimens is in excess of 220 MPa√m (200 ksi√in). This experimentally determined toughness is in good agreement with the 181 MPa√m (165 ksi√in) Kt value derived from the Rolfe-Novak relationship for the low-toughness region of the 22NiMoCr37 steel reported by the MPA. The toughness of the HAZ in the ITV-4 longitudinal weld was done. The EB technique was used to produce the crack in the desired area of the HAZ using the PC specimen. Because the propagation of the crack in ITV-4 ran through the center of the weld, it was necessary to weld extensions on the specimens using an electron beam. Tests were conducted at temperatures from -73°C (-100°F) to -18°C (-0°F). Fracture toughness values of 286 and 227 MPa√m (260 and 207 ksi√in) were obtained at -46°C (-50°F) and -18°C (0°F), respectively. These high toughness values, which are similar to those that can be expected for A 508 Class 2 base metal, were obtained in the HAZ of an A 508 Class 2 steel weldment that had undergone a strain of from 0.1 to 0.5% at 24°C (75°F).

Welding Procedures

The influence of welding procedures on the underclad cracks has been discussed in detail. Work on the influence of welding procedures on the sensitivity to GBD in butt welds has been considered but not to the same extent. The MPA correlated the incidence of reheat cracking to the coarseness of the HAZ. The coarser structure was attributed to higher heat inputs during welding. However, the MPA did point out that the grain size in the region of the HAZ from the ITV-4 prolongation (which, as the MPA reported, contained the largest microcracks that they had observed) was not the largest that they had found in their metallographic examinations.

Westinghouse Electric has examined the effect of heat input. They contracted with Combustion Engineering to prepare two SA welds, one
with low heat [2560 kJ/m (65 kJ/in.)] input procedure, the second with a high heat input [5120 kJ/m (130 kJ/in.)] between SA 508 Class 2 base metals. The SA 508 Class 2 heat of steel used by Mager and Thomas was known to exhibit underclad cracks.* They metallographically examined the HAZ of these weldments using the procedures developed by the MPA. They found no cracks in the HAZ of the low heat-input weld.

In the high-heat input weld, Mager and Thomas examined about 40 different areas and found GBD in about 4 or 5 areas. They removed samples from the weldment and prepared push-pull fatigue specimens that contained weld metal HAZ and base metal in the gage section. They determined a fatigue precrack state is existing.* The MPA expressed the fear that the small GBD may in fact mask a large reheat crack.

The reheat cracks (GBD) of the type mentioned above in the low heat input welding are extremely distinct or the material are extremely distinct or the adjacent dendrite of the deposit surface are often readily detected by nondestructive techniques, even if a refined ultrasonic method is being used. The MPA does note, however, that "ghost indications" may occur during the ultrasonic test, if the coarse-grain zone and the adjacent dendrite of the deposit material are extremely distinct or the precrack state is existing.* The MPA specifically state that the small GBD may in fact mask a large reheat crack.

The detection of discontinuities in large, thick-walled components by ultrasonic techniques (UT) is at best difficult, and the analysis of indications is even more of a problem. A number of factors must be considered when assessing the detectability of flaws; in addition to the vessel material being examined, these factors include the various electronic and mechanical parameters of the testing procedure.

The influence of probe size, frequency, and gain on the sensitivity of ultrasonic testing has been discussed by Klimpf and Canonico. They showed that the detectability of "ideally" sized discontinuities in commercial steel plate was strongly influenced by testing procedures. The location and geometric shape of the GBD also tend to minimize discontinuity detection. Further, the "cracks" are extremely tight and in many instances will not interfere with the ultrasonic wave.

The location and geometry of the GBD in the weldment will also influence detectability of discontinuities. Those GBD that extend to the surface are often readily detected by good magnetic-particle or dye-penetrant procedures. However, due to the factors responsible for the presence of the GBD, it is not likely that they will extend through the surface. The lack of restraint at this location will tend to minimize the probability of surface GBD.

The size and orientation of these GBD prohibit assurance of their detection by normal radiographic procedures. The normal detection limits suggested by the ASME Code for thickness changes in heavy-walled vessels is about 1%. In a 30.5 cm thick (12 in.) plate, this would represent a 3 mm (0.12 in.) distance between the free surfaces of the GBD. The extreme tightness of the GBD is illustrated in the photomicrographs in Fig. 8.

In summary, the probability of detecting GBD by NDE procedures is extremely small. Indeed, these procedures may interfere with the detection of larger flaws.

**Radiation Sensitivity**

One of the major considerations in assessing the integrity of a nuclear pressure vessel is its sensitivity to irradiation. This is particularly true of any region of a vessel, such as the HAZ, that is already suspect because of its atypical microstructure and its propensity to GBD.

The information that is directly applicable to the sensitivity of the HAZ of SA 533 Grade B Class 1 steel and SA 508 Class 2 steel is sparse. There is, however, information from which predictions of the toughness of the HAZ can be made. Serpan reported the shift of the HAZ toughness of 4 in. thick A 302 Grade B steel weldments. This steel, which has no requirement for nickel, is the predecessor of the A 533 Grade B Class 1 steel. This study showed that the HAZ underwent a smaller shift in transition temperature (TT) than either the base metal or weld metal after being irradiated to a fluence of 2.1 x 10^17 n/cm² (E > 1 MeV) at 288 C (550 F).

A similar response (low sensitivity of the HAZ to irradiation damage) was shown for the HAZ of an SA weld between two 150 mm thick (6 in.) plates of A 543 Class 1 steel. A 543 is a NiCrMo steel which has specified minimum yield and ultimate tensile strengths of 586 and 724 MPa (85 and 105 ksi), respectively. The A 543 steel is a more hardenable steel than the SA 533 Grade B or SA 508 Class 2 steels.
that are currently used in the fabrication of nuclear pressure vessels. Upon heat treating, this steel will transform to a low-temperature transformation product similar in microstructure to that of the HAZ of the two reactor pressure vessels steel being considered in this report.

In a study by Potapovs and Hawthorne involving the irradiation sensitivity of a more hardenable 200 mm thick (8 in.) pressure vessel steel, the steel underwent a lesser shift (40 C (105 F)) in its 40 J (30 ft-lb) C T than a 150 mm thick (6 in.) plate of A 502 Grade B steel [12 C (155 F)]. The A 543 Grade B steel was irradiated to a fluence of $10^{19}$ n/cm$^2$ (E > 1 MeV).

Williams and James investigated the effect of irradiation on the fracture toughness of A 533 Grade B Class 1 weldments. They employed 1T compact-tension specimens in their study. Their results indicated that the coarse-grained region of the HAZ had a radiation sensitivity similar to that of the weld metal and base metal. They especially commented on the high $K_{IC}$ (the equivalent energy method was used for calculating toughness) of the coarse-grained region of the HAZ.

An example of the influence of microstructure on the irradiation sensitivity of A 533 Grade B steel is shown in Fig. 18. These data are from the same heat of steel, a 305 mm thick (12 in.) plate of A 533 Grade B Class 1. The surface material which cooled during quenching from the austenitizing temperature at a rate ten times faster than that of the quarter- and mid-thickness locations shows much less shift in the 40 J (30 ft-lb) C T temperature. The 40 J C T temperature of the top surface shifted upward 27 C (80 F) after exposure to a fluence of $5 \times 10^{19}$ n/cm$^2$ (E > 1 MeV), whereas the quarter-thickness location underwent a 57 C (135 F) shift when exposed to a lower [4 $\times 10^{19}$ n/cm$^2$ (E > MeV)] fluence. These differences are due only to the variation in microstructure. Because of its faster cooling rate after austenitizing, the top surface contains a lower transformation product (lower bainite structure) than that observed at the quarter-thickness location.

Hawthorne and Steel in a study of the metallurgical variables that affect irradiation sensitivity concluded that "microstructure plays a dominant, if not the most influential role in radiation sensitivity development," and "a tempered martensite structure is generally less radiation sensitive than tempered upper bainite or ferrite structures."

These data indicate that the lower transformation product undergoes a lesser loss of toughness as a consequence of irradiation to fluence levels that are typical of those to which a pressure vessel for a pressurized-water reactor will be exposed during its design lifetime.

This information tends to suggest that the microstructure of the coarse-grained region of the HAZ is representative of a low-transformation product (martensite or lower bainite) and will be less sensitive to irradiation than the base metal. This conclusion is supported by the toughness data (admittedly scant) that are available for the HAZ after irradiation to fluence levels of about $2-3 \times 10^{19}$ n/cm$^2$ (E > 1 MeV).

Conclusion

It is highly probable that there are nuclear pressure vessels in service today that contain GBD in the HAZ of their structural welds. Further, it is more likely that GBD exist in vessels fabricated from SA 508 Class 2 than those fabricated from SA 533 Grade B Class 1 steel. This fact is due to the higher propensity of the SA 508 Class 2 analysis to stress-relief cracking. If these GBD exist in nuclear pressure vessels, they would not be detected by the nondestructive examination procedures currently employed commercially throughout the world during vessel fabrication and surveillance. The GBD reside in an extremely localized region of the HAZ. The area of interest is only about two to four grains wide [about 0.381 mm (0.015 in.)], and it is difficult to determine toughness values that represent the properties in this region.

There has been a considerable amount of work done trying to determine the $C_T$ and $K_{IC}$ toughness of this region. Most results indicate that this region is superior or at least equal to that of the base metal. These observations are supported by studies that indicate that, when correctly tempered, the fracture toughness of the lower transformation product (martensite) is superior to that of tempered bainite. The microstructure in the region of the HAZ that contains the GBD is tempered martensite or tempered lower bainite.

The relationship between austenite grain size and toughness is complex. There is a correlation that shows that a microstructure containing coarse austenitic grain size has poorer toughness than one that contains fine austenite grains. In this case, the coarser austenite grains can indeed be beneficial because they promote the transformation of the steel to martensite, and
tempered martensite has better toughness properties than tempered bainite. Further, the tempered martensite (lower transformation product) is more radiation resistant than tempered bainite. This observation tends to nullify the concern that the coarse-grained region of the HAZ may be more sensitive to irradiation.

Obtaining definitive $C_N$ toughness data in the coarse-grained region of the HAZ is difficult. The placement of a 0.254 mm radius (0.010 in.) notch in the correct location is at best hit and miss. The notch-tip radius is approximated by the same size as the area of interest. Further, the fusion line is not straight, which also contributes to the difficulty of notch placement.

The fracture-mechanics specimens and compact-tension specimens depend on fatigue cracks for their correct toughness values. Growing a fatigue crack in the area of interest is extremely difficult. First, there is the problem of placing the machined notch in the desired location. Second, during fatigue, the propagating crack will seek the best microstructure, which is not the coarse-grained region of the HAZ.

There has been an opportunity during the past two years to investigate the HAZ of ITV-4, a vessel which was tested to destruction at 24°C (75°F). This study was prompted by a report from the MPA that they had examined from the MPA that they had observed to date. The vessel containing the largest microcracks that they had observed to date. The vessel was subjected to 0.5% in the vicinity of the longitudinal weld. This vessel was pressurized for testing over three times the ASME Code (Section III) allowable design pressure prior to failure.

During testing, acoustic emission nondestructive testing techniques were employed, and no evidence of crack extension in the HAZ was indicated. The HAZ from the longitudinal weld was metallographically examined. Grain boundary decohesions were found, but there was no evidence of crack extension in spite of the large strains imposed on the vessel during testing.

It must be emphasized that this review has been concerned with the steels that are currently found in nuclear pressure vessels, namely SA 508 Class 2 and SA 533 Grade B Class 1 and their similar predecessors.

As a consequence of this review, the following conclusions are offered:

1. The probability that grain boundary decohesions (GBD) do exist in the heat-affected zone (HAZ) of nuclear pressure vessels is quite high.
2. There is evidence, supported by both experimental data and metallurgical interpretation that the fracture toughness of the HAZ containing the GBD is equal to or superior to that of the base metal. The experimental data obtained from tests conducted on the HAZ of actual welds, not determined from microstructures generated by simulating welding procedures.
3. The radiation resistance of the region of the HAZ that contains GBD is probably superior to that of the base metal.
4. A region in the HAZ of ITV-4 that was extremely sensitive to the formation of microcracks, and one which did indeed contain them, did not exhibit a propensity to crack extension even after being strained to levels as high as 0.5%.
5. The subcritical crack growth rates, $da/dN$, in the HAZ do not appear to be significantly different from those of the base metal. However, this is a subject about which very little is known.
6. A crack which initiated in the weld metal of ITV-4 did not extend into the HAZ but instead continued to propagate through the centerline of the weld.
7. There is a lack of definitive information, particularly on the fracture toughness of the HAZ of SA 508 Class 2 weldments. Most studies to date have been conducted on SA 533 Grade B Class 1 steel, a steel that is less sensitive to reheat cracking than the forging grade. The information gathered during this review, and the experimental data obtained at ORNL, indicate that the pressure vessel integrity is not jeopardized as a consequence of the presence of GBD in the coarse-grained region of the HAZ. This conclusion should be supported by fracture toughness tests designed specifically to measure the properties of the coarse-grained region of the HAZ both in the unirradiated and irradiated conditions.

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