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Fissuring in the "Hazard HAZ" Region of Austenitic Stainless Steel Welds

A relatively low ductility region is found in the weld metal of previously deposited weld beads from multipass or repair welding where fissuring can occur when ferrite is under 1 FN and when the imposed strain exceeds the strain tolerance of the microstructure

BY C. D. LUNDIN AND C. P. D. CHOU

ABSTRACT. The potential for HAZ hot cracking in ferrite-containing and fully austenitic weld metals is discussed and contrasted to solidification hot cracking. A theory and mechanism for HAZ cracking, which occurs in underlying weld beads, is presented for both the ferrite-containing and fully austenitic welds.

A "Hazard HAZ" region is documented as existing in the weld metal of a previously deposited weld bead, adjacent to, but not contiguous with the fusion zone of the deposited bead under consideration. This "Hazard HAZ" region can exhibit relatively low ductility and fissures can occur if the ferrite content is below approximately 1 FN (1%), and the strain imposed exceeds the strain tolerance of this local microstructural region.

The cause of the low ductility in the "Hazard HAZ" region is the embrittlement of the austenite grain boundaries. This embrittlement can be partially explained by utilizing a Fe-Cr-Ni pseudo-phase diagram. In the ferrite-containing weld, the ferrite dissolves below the γ-solvus and then reforms above the γ-solvus upon heating. Ferrite has a greater solubility than austenite for certain "harmful" elements, such as Si, P, and S which are related to the cause of fissuring. As the ferrite transforms to austenite (γ), these "harmful" elements are released and redistributed at the grain boundaries, thus reducing the local ductility.

It is in these degraded austentite grain boundaries, where the ductility is decreased compared to the adjacent grain interiors, that cracking occurs. For the fully austenitic stainless steel weld metals, the fissuring propensity becomes significant as the weld metal is reheated to a high temperature by subsequent weld passes. Due to the absence of ferrite in the austenite matrix, the grain boundary segregation of the "harmful" elements is unrestricted, and the concurrent grain growth which occurs during reheating reduces the grain boundary area, thus enhancing segregation and unfavorably influencing the fissuring propensity.

Introduction

The hot cracking tendency of austenitic stainless steel weld metals (fusion zone) and HAZ has been the subject of many intensive investigations over the past 15 years. The research has concentrated on the hot cracking attendant upon solidification and has isolated the solidification mode (primarily ferrite-primarily austenite) as the most important factor in the cracking mechanism.

The most promising means of solidification cracking control is the choice of a composition that fosters ferritic solidification. The role of ferrite in mitigating against hot cracking has been long recognized, but the most recent work has placed the relationship of solidification mode/ferrite in perspective and has helped to explain why ferrite control/measurement in the room temperature microstructure is a means of reducing cracking potential.

However, solidification cracking is not necessarily the most important form of hot cracking in stainless steels. Cracking in the underlying welds or in the base metal adjacent to the fusion zone is often more common and thus more important from the practical standpoint. This HAZ cracking has been recognized (Refs. 1-8) but not extensively investigated until the work of Lundin, Spond, and DeLong

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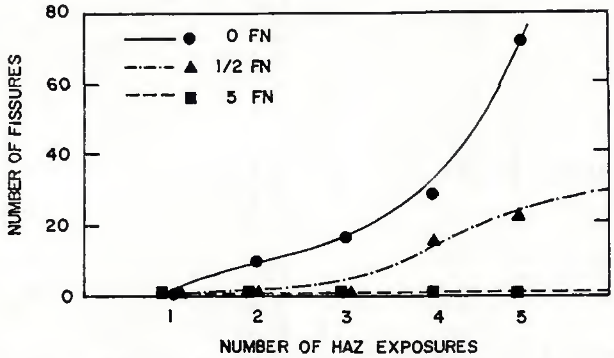

Fig. 1—Fissure bend test results-multiple HAZ exposures produced by autogenously GTA remelted weld deposits

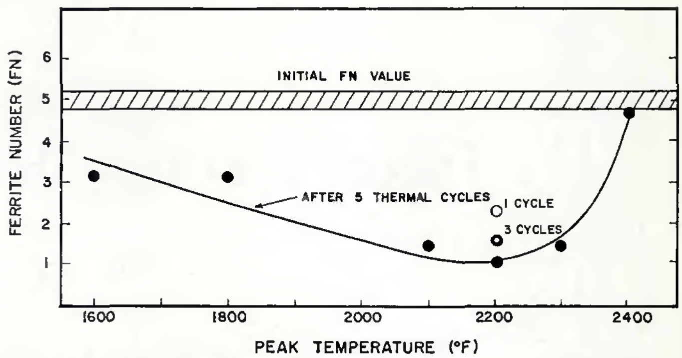

Fig. 2—Effect of peak temperature on the ferrite number of austenitic stainless steel weld metal L

(Refs. 9-11), based on the fissure bend test, was published in 1975-76. Since that time, continued research sponsored by the Welding Research Council at The University of Tennessee, has been directed at the HAZ cracking phenomenon (Refs. 12, 13). The culmination of a portion of this work, concentrating on HAZ cracking, is reported on herein. A new concept of a "Hazard HAZ" region is proposed and detailed with regard to both ferrite-containing and fully austenitic weld metal HAZ's.

Results and Discussion

Some HAZ/Ferrite Content/Cracking Relationships

The earlier work of Lundin, Spond and DeLong (Ref. 12) found that the number of thermal cycle exposures to which a previous weld bead was subjected caused an increase in the cracking tendency. The cracking potential was also influenced by the ferrite content of the underlying weld run.

Figure 1 presents data obtained as a function of the number of HAZ exposures and ferrite level. From these data it is clear that the low ferrite welds are more sensitive to cracking than the high ferrite welds as the number of HAZ exposures is increased. Metallographic examination of the fissured welds showed that the fissures occurred in a zone adjacent to, but not contiguous with, the fusion zone of the weld bead producing the HAZ exposure.

Through the use of HAZ thermal history measurements, Spond and Lundin (Ref. 11) established the cracking temperature range to be from 1950°F (1065°C) to 2400°F (1315°C). Further, it was recognized that the ferrite level in the fissured region of the weld metal HAZ was lower than that of the bulk of the deposited weld metal. These determinations prompted the research into the conditions related to the fissuring and its unique location in the HAZ.

"Gleeble" Studies

Using the "Gleeble" to duplicate HAZ thermal histories adjacent to the weld fusion line, the ferrite level was determined as a function of peak temperature, cooling rate and the number of HAZ thermal exposures. Two weld metal ferrite levels were chosen for this study; a high ferrite (FN25) and a low ferrite (FN5). Weld metal samples were cycled up to 5 times to a range of peak temperatures and the ferrite level measured at room temperature. Helium blast (accelerated) cooling was used to "freeze in" the ferrite present at the elevated temperature during the thermal cycle.

The results of the determinations are presented in Figs. 2 and 3 for the low ferrite weld metal and in Fig. 4 for the high ferrite weld metal. Figure 2 shows the ferrite number (FN) as a function of peak temperature. It is clearly noted that the ferrite content decreases as the peak temperature of the thermal cycle is increased to 2200°F (1204°C) and then rises again as the temperature exceeds 2200°F (1204°C). The effect of the number of cycles (*i.e.*, 1, 3 and 5) is shown, indicating that as the number of cycles increase the ferrite level drops (beyond 5 cycles little change in ferrite magnitude is evident).

Figure 3 shows the same data (solid curve) and the influence of rapid cooling on the ferrite level. It is to be noted that the cooling rate does not influence the ferrite level until 2200°F (1204°C) is exceeded; the ferrite level then increases to beyond the amount present in the original weld. The minimum in the ferrite level still occurs at about 2200°F (1204°C).

The response of the "high" (H) ferrite level weld metal is shown in Fig. 4 in the same manner as the "low" (L) ferrite shown in Fig. 3. The reduced ferrite region is not as pronounced and the increase in ferrite induced by rapid cooling occurs over a wider range of temperatures.

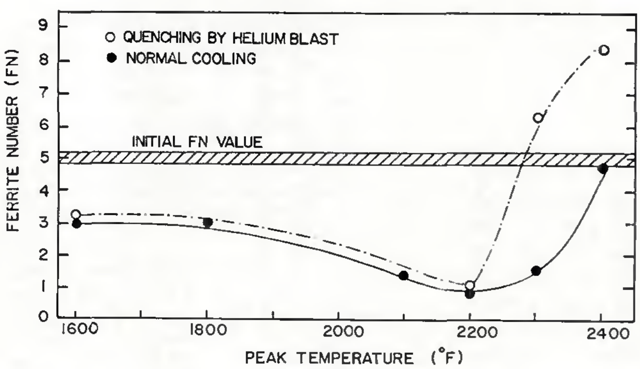

Fig. 3—Effect of peak temperature and cooling rate on the ferrite number of austenitic stainless steel weld metal L

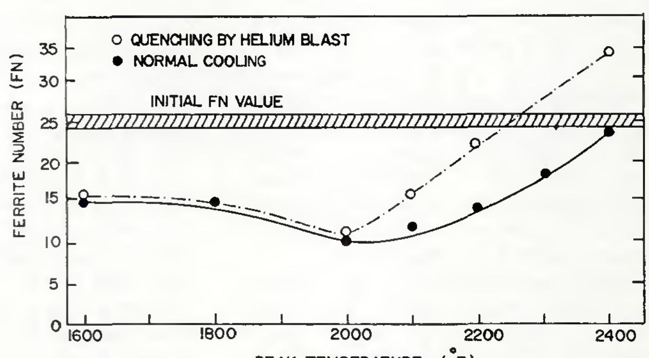

Fig. 4—Effect of peak temperature and cooling rate on the ferrite number of austenitic stainless steel weld metal H

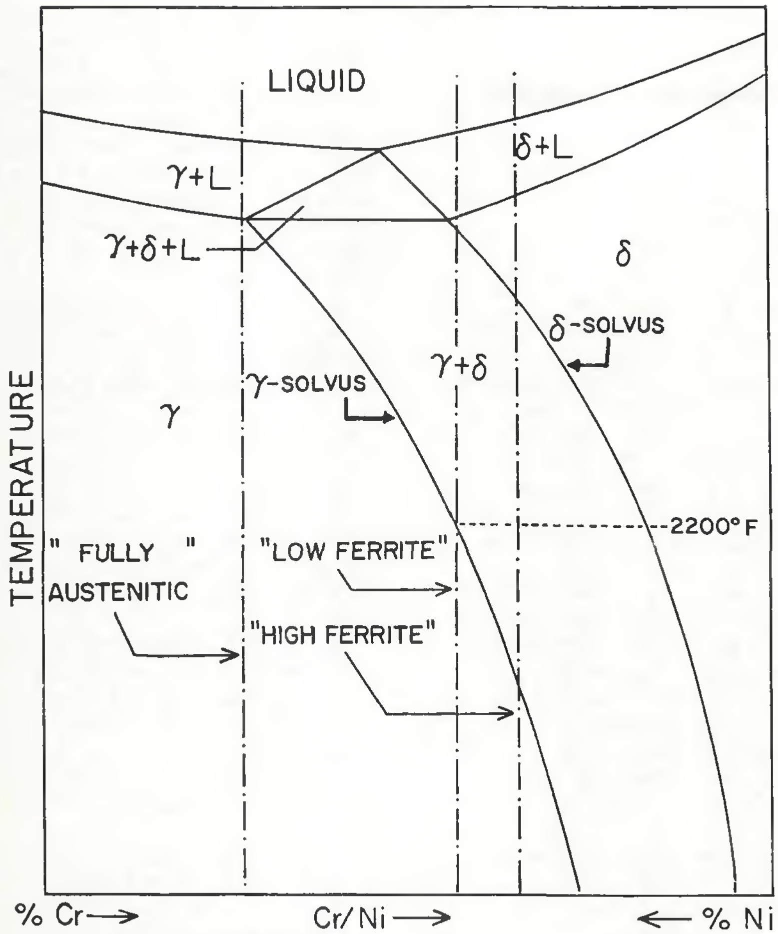

Fig. 5 — Fe-Cr-Ni pseudo-binary diagram

Ferrite Content/Temperature Change Effects

The temperature range over which the ferrite level is reduced corresponds well with the observations of the cracking behavior adjacent to weld beads as was previously found. The fact that the ferrite content decreases with the number of thermal cycles of HAZ exposure also correlates well with the data in Fig. 1 and that of Lundin and Spond (Ref. 11). The ability of the thermal cycle simulation device (*i.e.*, "Gleeble") to expand the HAZ region of interest to a larger affected volume gives rise to the simpler measurement of the ferrite levels in the HAZ. (Very narrow regions in actual weld HAZ's do not permit magnetic determination of ferrite as a function of location.)

The reduction of ferrite as the HAZ peak temperature is increased to a certain temperature and then the increase in ferrite as the temperature is raised further can be explained by reference to the Fe-Cr-Ni pseudo-binary phase diagram in Fig. 5. On this diagram are shown three alloys — the low ferrite (5 FN), high ferrite (25 FN) previously discussed, and a fully austenitic alloy also investigated.

For the weld metal with approximately 5 FN residual ferrite (L), Fig. 5 shows that, as the weld metal is reheated to temperatures below the γ-solvus temperature (2200°F, *i.e.*, 1204°C), the residual ferrite should transform to austenite (γ) by a solid state diffusion controlled reaction. The higher the temperature (but below the γ-solvus, 2200°F, *i.e.*, 1204°C), the faster the dissolution of ferrite should become, because the diffusion rate increases rapidly with temperature. In addition, as the number of thermal exposures increases, the ferrite level decreases for temperatures below the γ-solvus — Fig. 2.

The decrease in ferrite is time-dependent, because resolution is diffusion controlled and the initial solidification segregation magnitude in both austenite and ferrite is also a factor in the rate of dissolution of ferrite. The ferrite reduction in the temperature regime below the γ-solvus is permanent, and the ferrite level in the microstructure will not increase unless a thermal cycle is imposed which raises the temperature above the γ-solvus.

As the temperature is increased above the γ-solvus, delta ferrite should reform. The delta ferrite content will increase as the temperature is increased above the γ-solvus. The "new" delta ferrite, which will preferentially form on any remaining ferrite or will renucleate at grain boundaries, can be retained if the temperature is decreased rapidly by quenching (as with a helium blast) after reaching a given peak temperature.

Reformed delta ferrite will partition the alloying elements in accord with the austenite and delta ferrite solubilities. This repartitioning will reduce the concentration of the "harmful" elements (*i.e.*, Si, S, and P) in the grain boundaries. However, the reprecipitated delta ferrite may transform back to austenite upon cooling, especially as the cooling rate decreases. Normal weld cooling rates permit some transformation on cooling.

In the high ferrite weld metal (H), time-temperature exposure below the γ-solvus will need to be longer to dissolve the ferrite produced upon solidification (and subsequently retained) because of the enhanced ferrite level and the greater degree of segregation produced upon solidification. Further, for the high ferrite weld metal, the γ-solvus is intersected at a lower temperature, and the alloy tends toward a fully ferritic structure as the solidus temperature is approached. The behavior shown in Fig. 4, with regard to the ferrite-temperature relationship, directly reflects the phase diagram predictions.

The fully austenitic weld metal contains no ferrite and does not form ferrite upon thermal cycling. Therefore, the ferrite transformation has no influence on such materials. Thus, the grain coarsening and grain boundary segregation effects attendant upon heating should control the hot cracking behavior.

Determination of "Hazard HAZ" Region

If the ferrite content of a weld HAZ is expressed as the fraction of remaining ferrite and as a function of HAZ peak temperature, the data presentation shown in Fig. 6 results. A dashed line at 50% remaining ferrite is used to illustrate the region of the HAZ where the ferrite is reduced to a level such that a significant increase in hot cracking sensitivity could result. If the "Hazard HAZ" region defined by the reduction of ferrite below 50% of the normal level is at an absolute ferrite amount less than 1 FN, a definite tendency toward hot fissuring will result — Fig. 1. The ferrite reduced HAZ region is susceptible to hot cracking when the combined influence of the amount of P, S, and Si together with the weld restraint exceeds some critical magnitude and the ferrite falls below approximately 1 FN.

A schematic summary of the above discussed phenomenon is shown in Fig. 7.

The phase diagram projection shows why the "Hazard HAZ" region is located slightly away from the fusion zone as postulated in the earlier work (Ref. 11). The ferrite morphology change as a function of location in the HAZ was documented in the "Gleeble" studies as illustrated in Fig. 8 for the low ferrite alloy.

In actual multipass welds, the decreased ferrite "Hazard HAZ" region is normally too narrow (0.030 in., *i.e.*, 0.76 mm) to be detected by any conventional magnetic instrument. This may also be the reason why many investigators have overlooked this phenomenon. However, by carefully observing the HAZ microstructure morphology, the ferrite decrease and morphology modified region in actual multipass welds was found—Fig. 9.

The GTA weld bead at the right in Fig. 9 was fused 5 times, thus producing a 5 cycle HAZ in the adjacent weld structure. The reduced ferrite level region can be seen, and the change in ferrite morphology is evident near the fusion line. The ferrite morphology change in regions of the HAZ subjected to temperatures above and just below the γ-solvus is extensive, indicating significant solute redistribution and renucleation of ferrite at locations different from those of the solidification induced ferrite.

The observations from actual welds and in the "Gleeble" simulated HAZ's (Fig. 8) are consistent with the occurrences and with the theory and mechanisms proposed herein.

Theory and Mechanism for Hot Cracking in the Reheated Weld Metal Passes

Ferrite-Containing Weld Metals

In multipass, ferrite-containing welds there is a HAZ region which is separated somewhat from the fusion line of a given bead; here the ferrite content is lower when compared with immediately adjacent HAZ areas. This region exhibits a lower ductility than the surrounding material, and fissures can occur if the strain imposed upon the weld exceeds the strain tolerance of this local microstructural region. This region has been named the "Hazard HAZ".

The cause of the decreased ductility in this region is the embrittlement of austenite grain boundaries. This embrittlement can be partially explained by utilizing the schematic Fe-Cr-Ni pseudo-phase diagram shown previously in Fig. 5. The approximate relative locations of "low ferrite" and "high ferrite" compositions are indicated by the vertical labeled lines.

For the low ferrite potential material, it can be seen that as the material is reheated to temperatures below the γ-solvus, any residual ferrite should tend to transform to austenite by a solid state reaction. Ferrite, having a higher solubility for elements such as S, P, and Si (which are known to adversely affect hot cracking) releases these elements as it transforms to austenite. These "released harmful elements" are redistributed by diffusion and grain boundary migration to the austenite/austenite grain boundaries, degrading their ductility and enhancing fissuring tendency.

As the temperature rises above the γ-solvus, "new" delta ferrite forms at existing ferrite and at the austenite/austenite grain boundaries and "reabsorbs" the "harmful" elements. Upon cooling, when the temperature drops below the γ-solvus, the ferrite tends to retransform back to austenite, leaving behind the "harmful" elements trapped at the austenite grain boundaries (ferrite/austenite interfaces become austenite grain boundaries upon ferrite transformation).

It is in the austenite grain boundaries degraded by the presence of P, S, and Si, that the ductility is decreased when compared to the adjacent grain interiors. The region which experiences the above phenomena and has a decreased ferrite content with lower ductility is the "Hazard HAZ."

For a high ferrite potential material, the "Hazard HAZ" region is narrower when compared to the lower ferrite potential material. In order to obtain a high ferrite

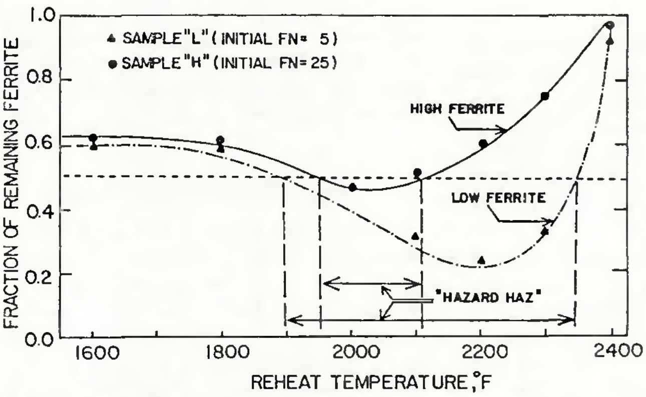

Fig. 6—Effect of preheat temperature on the fraction of ferrite remaining in austenitic stainless steel weld metal

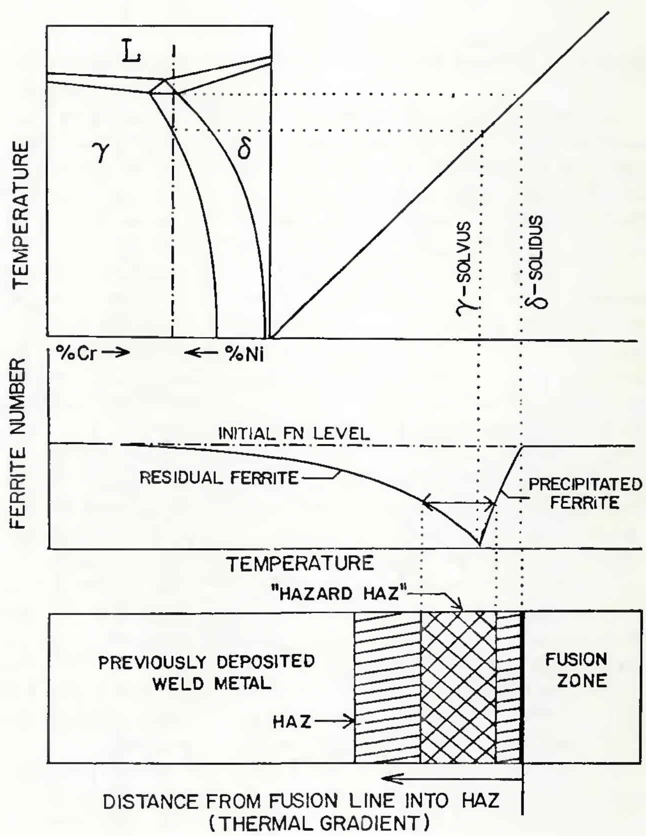

Fig. 7 (right)—Schematic location of "Hazard HAZ" region and its relationship to the phase diagram

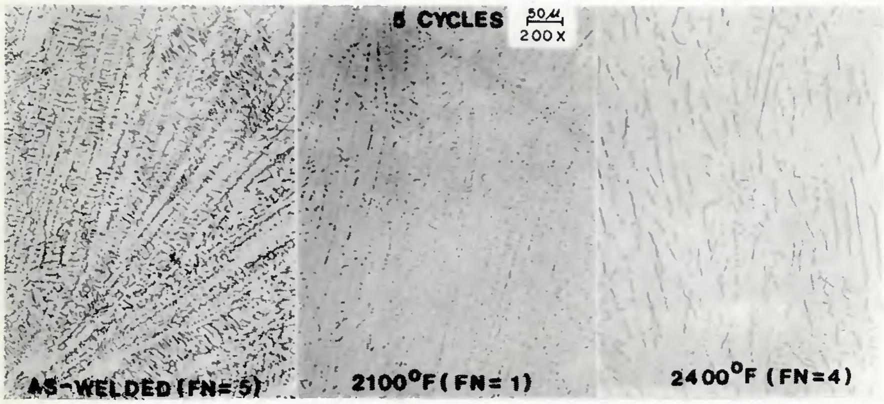

Fig. 8 — Microstructure of weld metal L (5 FN) as-welded and thermal cycled five times to 2100 and 2400°F (1149 and 1316°C)

potential material, the Cr/Ni ratio is increased at constant Fe content. Therefore, the vertical line representing the high ferrite potential composition in Fig. 5 is shifted to the right and the intersection with the γ-solvus line decreases in temperature.

Since the γ-solvus temperature is lower for the high ferrite material, a narrower "Hazard HAZ" is predictable for the high ferrite weld metal. The narrower region coupled with a higher ferrite content (recall that the reduced ferrite level should be below approximately 1% for a significant tendency toward hot cracking) greatly reduces the hot cracking potential.

In summary, a narrow weld metal "Hazard HAZ" region, separated from the fusion line of a given weld bead, exists in ferrite containing weld metal. The "Hazard HAZ" region may exhibit a lower ductility than the surrounding areas and fissuring may occur in this region under welding conditions imposing sufficient restraint. The extent (width) of the "Hazard HAZ" and the ferrite level therein depends upon the ferrite potential of the welding consumable used and the thermal conditions induced by welding.

Fully Austenitic Weld Metals

Since no ferrite exists in fully austenitic weld metals, an alternative explanation for the propensity toward HAZ hot cracking in these alloys is necessary and is proposed.

For fully austenitic stainless steel weld metals, the fissuring propensity becomes significant as the weld metal is repeatedly reheated as in repair or multipass welding. Due to the absence of ferrite in the austenite matrix, the grain boundary segregation of certain "harmful" elements and grain growth during the thermal cycling are the major factors influencing fissuring propensity.

After initial solidification of a fully austenitic weld bead, "harmful" elements such as P, S, and Si are segregated in the interdendritic regions. When the weld metal is reheated to a high temperature by a succeeding pass, grain boundary migration and grain growth occurs. The grain boundaries moving through the material during grain growth have a tendency to "sweep up" and enhance the segregation of the harmful species and to trap them in the grain boundaries. Since diffusion is temperature- and time-dependent, diffusion enhanced by reheating and the occurrence of multiple thermal cycles exacerbates segregation. The segregation of certain elements (P, S, and Si in particular) to grain boundaries is responsible for decreased ductility. Therefore, hot ductility can decrease significantly and intergranular fissures can occur when the strain intolerance is exceeded during the cooling portion of the thermal cycle in an actual weld.

The temperature range in which the ductility is decreased to the greatest extent ranges from approximately 1800°F (982°C) to the solidus tempera-

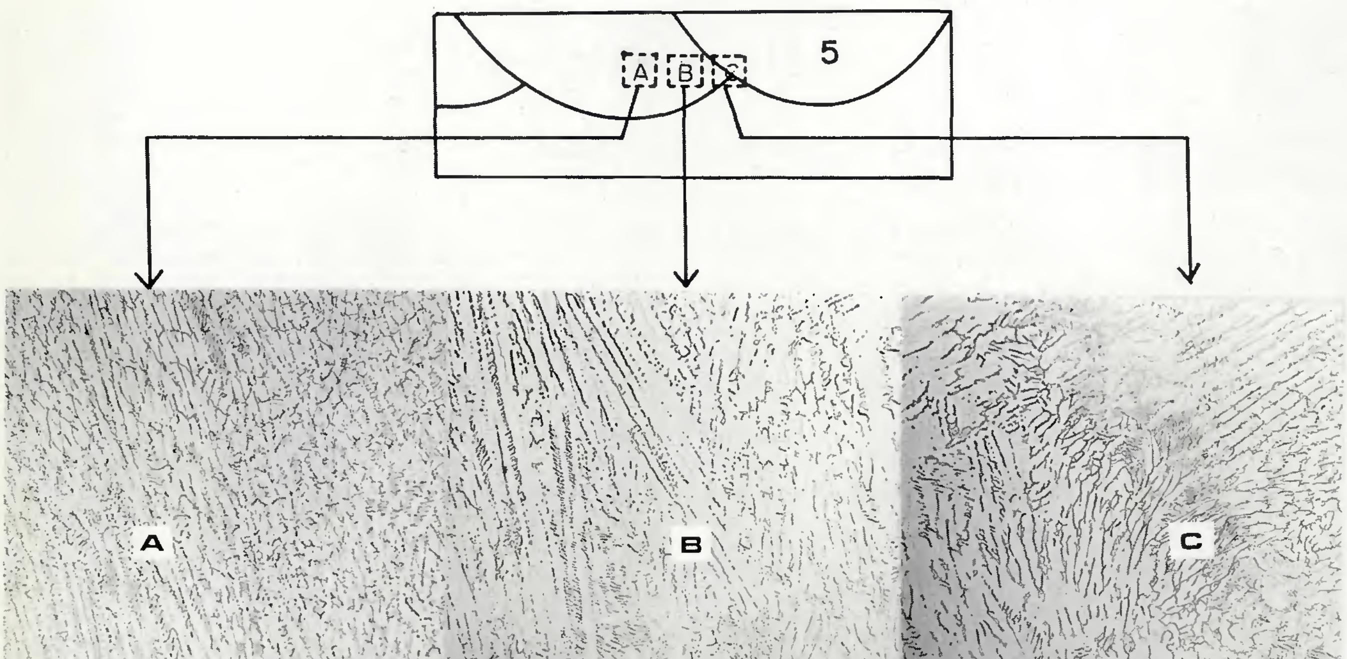

Fig. 9 — Microstructure in the region of the weld metal HAZ which experienced five thermal cycle exposures. Initial FN reduced from 5 to 1 in area B. X200 (reduced 29% on reproduction)

ture. Thus, the "Hazard HAZ" region in the fully austenitic weld metals is generally more extensive than in the ferrite-containing welds. Therefore, the probability of fissuring in the weld HAZ in fully austenitic welds is higher than in ferrite-containing welds.

Conclusion

A theory of hot cracking in the reheated regions of weld metal deposits in both multipass welds and repair welds is proposed. A region termed the "Hazard HAZ" exists near the fusion zone of a subsequent weld bead, and this region can exhibit low ductility. Fissures can occur in the Hazard HAZ region when the ferrite is reduced below approximately 1% for ferrite-containing welds and in all regions of the HAZ above 1800°F (982°C) in the fully austenitic weld, provided sufficient restraint is imposed by the structure and the welding conditions employed.

The extent of the "Hazard HAZ" region depends primarily on the composition of the weld metal with respect to the Cr/Ni ratio combined with the Cr content, as well as the Mn + Mo levels. The degree of degradation of the grain boundary ductility is dependent on the P, S, and Si contents coupled with the number of HAZ exposures.

Acknowledgment

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References

1. Haddrill, D. M., and Baker, R. G. 1964. Microcracking in austenitic weld metal, *Weld. Research Abroad*, Vol. 12, no. 1:43-51.
2. Honeycombe, J., and Gooch, T. J. 1970. Microcracking in fully austenitic stainless steel weld metal. *Metal Construction and Brit. Welding J.* 2(9):375-380.
3. Honeycombe, J., and Gooch, T. G. 1975. Microcracking in fully austenitic stainless steel weld metal. *Metal Construction and Brit. Welding J.* 7(3):146-148.
4. Burghard, H. C., Norris, E. B., Pickett, A. G., and Watson, P. D. 1971. *An investigation of the properties of Type 316 stainless steel weldments containing austenitic microfissures.* SWRI topical report no. 1, project 17-3078, August 15, 1971.
5. Buchhoit, R. D., Jaske, C. E., and Bennet, R. W. 1971. *Laboratory studies of Type 316 stainless steel weld metal from Maine Yankee reactor coolant system.* Battelle final report, September 17, 1971.
6. Thielsch, H. 1972. *Examination of Type 316 stainless steel weld deposit for microfissuring and delta ferrite contents for Oconee nuclear power station, Duke Power Company.* Report no. 1057, December 23, 1972.
7. Gooch, T. G., and Honeycombe, J. 1980. Welding variables and microfissuring in austenitic stainless steel weld metal. *Welding Journal* 59(8):233-s to 241-s.
8. Witherell, C. E. 1980. Welding stainless steels for structures operating at liquid helium temperature. *Welding Journal* 59(11):326-s to 342-s.
9. Lundin, C. D., Spond, D. F., and DeLong, W. T. 1975. Ferrite fissuring relationships in austenitic stainless steels. *Welding Journal* 54(8):241-s to 246-s.
10. Lundin, C. D., Spond, D. F., and DeLong, W. T. 1976. The fissure bend test. *Welding Journal* 55(6):145-s to 151-s.
11. Lundin, C. D., and Spond, D. F. 1976. The nature and morphology of fissures in austenitic stainless steel weld metals. *Welding Journal* 55(11):356-s to 367-s.
12. Lundin, C. D., Chou, C. P. D., and Sullivan, C. J. 1980. Hot cracking resistance of austenitic stainless steel weld metals. *Welding Journal* 59(8):226-s to 232-s.
13. Lundin, C. D., and Chou, C. P. D. 1983. *Hot cracking of austenitic stainless steel weld metals.* WRC bulletin no. 289, November 1983. New York: Welding Research Council.

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Long-Range Plan for Pressure-Vessel Research—Seventh Edition
By the Pressure Vessel Research Committee

Every three years, the PVRC Long-Range Plan is up-dated. The Sixth Edition was widely distributed for review and comment. Up-dated problem areas have been suggested by ASME, API, EPRI and other organizations. Most of the problems in the Sixth Edition have been modified to meet current needs, and a number of new problems have been added to this Seventh Edition.

The list of "PVRC Research Problems" is comprised of 58 research topics, divided into three groups relating to the three divisions of PVRC; i.e., materials, design and fabrication. Each project is outlined briefly in a project description, giving the title, statement of problem and objectives, current status and action proposed.

Because of budget limitations, PVRC will not be able to investigate all of these problems in the foreseeable future. Therefore, the cooperation and efforts of other groups in studying these areas is invited. If work is planned on one of the problems, PVRC should be informed in order to avoid duplication.

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