Avoiding Weld-Related Failures in Austenitic Stainless Steels

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Abstract: The austenitic stainless steels are easily fabricated by arc welding processes and develop excellent as-welded properties. To prevent degradation of the structural and corrosion resisting properties of the base metals, care must be taken in the design, materials selection, and procedures when weld fabrication is undertaken. In addition to the requirements of the application and welding/fabrication techniques, adequate knowledge of the metallurgical aspects of the base metals, heat-affected-zones, and weld metal on the structural and corrosion resistant properties is also essential to successful arc welding of the austenitic stainless steels.

Introduction: Austenitic (300 series or Cr-Ni) stainless steels in sheet, strip, and tubular forms have been selected for a wide variety of applications. Even though coated steels, aluminum, titanium, plastics, and ceramics are better alternatives in certain environments, the combination of good mechanical properties from cryogenic temperatures to elevated temperatures, corrosion resistance, ease of fabricability, and economy is unique. The excellent fusion (or arc) weldability of this class of steels is realized daily at the steel plants during production, at the fabricator's shop, in construction, and during maintenance work.

Discussion of Weldability: The forgiveness of these steels during welding is principally attributable to the following characteristics: relative insensitivity to hydrogen embrittlement, toughness over a wide range of temperatures, essentially a single-phase structure during heating, high solubility for many undesirable elements, good ductility and toughness in the cast condition, compatibility with other stainless steels of the same class, low melting point, and resistance to notch effects.

To the weld fabricator, these characteristics translate to advantageous practices such as:

1. minimal preheat requirements;
2. interpass temperatures up to 600F are often tolerable;
3. retarded cooling rates to prevent cracking are unneeded;
4. contamination of the weld joint often does not cause weld integrity problems (but could affect corrosion resistance);
5. ability to straighten or form the weldment;
6. post weld heat treatments are often unnecessary;
7. ability to use the most economical mix of such alloys within the same component; and
8. many types of minor weld defects can often be tolerated without jeopardizing the structural integrity.

Compared to other steels, however, certain attributes of the austenitic stainless steels create the need for special precautions during fusion welding to prevent problems. All the stainless steels utilize chromium as the major alloying addition to develop oxide films for corrosion resistance and high temperature oxidation resistance. The existence of highly oxidizable elements such as chromium, though, requires the use of inert shielding gases during welding to avoid arc instability problems, facilitate post weld cleaning of the weldment, and avoid absorption of detrimental quantities of nitrogen. More rigid fixturing or post weld straightening are also common due to the combination of relatively low thermal conductivity and high coefficient of expansion that together cause distortion during welding and solidification.

Also, the austenitic stainless steels can be prone to a welding phenomenon called "hot cracking". This defect manifests itself as small cracks that form in the weld at high temperatures during cooling. It appears first in weld craters then, if severe, at the weld centerline and occasionally along the weld centerline but oblique to it (Figure 1). When present, such cracks can be easily identified with dye penetrant techniques, if not visually. The cause of such cracks involves planes of weakness in the cast structure that rupture as the solidifying structure creates stresses approaching the yield point. These planes exist because of concentrations of residual tramp elements, mainly phosphorus and sulfur, that have segregated during solidification to interdendritic sites and form low-melting compounds.(1,2,3,4)

The steelmakers and welding consumable suppliers have learned how to minimize concern for "hot cracking" in many of the austenitic stainless steels by balancing the chemistry to permit a small amount of a second phase, ferrite, to form during solidification. Existence of this phase dilutes the concentration of these compounds by increasing the grain boundary size, providing greater solubility for such elements, and providing a discontinuous network of such compounds, since these compounds preferentially segregate to the boundaries of this phase. However, due to the specification limits of alloys like Type 310 and the detrimental effects of ferrite for certain cryogenic(5,6) and high temperature(7,8) applications, special steelmaking practices are necessary to minimize the contents of P and S for such applications, since the existence of ferrite in the solidified weld deposit is prohibited. Most all the commodity austenitic stainless steels (i.e. Types 301, 304, 304L, 316, 316L) are balanced for ferrite formation to negate the detrimental effects of these tramp elements.

Why Problems Arise: Despite the excellent fusion weldability of the austenitic stainless steels, a small percentage of such weldments are involved in fabrication and service failures. Although many problems do arise because of a lack of welder skill, most of the failures are a direct result of inadequate knowledge by those designing the component, by those specifying or procuring the material, or by those responsible for determining the welding procedures and practices. Proper materials selection requires knowledge of the service environment and needed material attributes. Also, field fabrication restrictions often impact such choices. As an example, a low carbon alloy should be chosen for certain corrosive environments when welding is required in field fabrication where post weld heat treatment is impractical.(9) To successfully overcome the obstacles posed by a given application, adequate sources of metallurgical, corrosion, structural, and welding process expertise are necessary in the planning stages.

Weld Fabrication Problems: Fabricating failures usually involve ignorance of the formability characteristics of a given weldment, of the effects of contamination at the weld joint, of proper welding procedures, or of required attributes of the weldment for the service environment. This is especially true in non-routine situations, such as welding dissimilar materials, where inappropriate generalizations are sometimes made. Complex requirements also cause problems when it becomes impossible to achieve all the characteristics specified, such as designing a complicated component that requires final machining with close tolerances prior to extensive welding. Designing weld fixturing to prevent loss of dimensions from the distortion caused by welding, which can be considerable for austenitic stainless steels, is often impossible in such instances.

Weld fabrication failures occur during welding, during subsequent forming, or during testing and are most often detected visually or via non-destructive test methods, such as dye penetrant inspection. The more common types of problems with austenitic stainless steel weldments can be categorized as general weld quality, hot cracking, and contamination. Due to the greater volume weld fabricated by the automatic welding processes, especially G.T.A. (gas tungsten arc) tube welding, compared to manual or semi-automatic processes, the general weld quality defects of the former have been given more attention.

Although proper automatic G.T.A. welding practices have been fairly well publicized, tube manufacturers occasionally run into porosity problems, weld slagging problems, incomplete penetration, undercutting, humps, and center cavities. For automatic G.T.A. welding, the austenitic stainless steels must be welded at reduced travel speeds. In fact, a fairly tight relationship exists between travel speed and welding current (Figure 2) to avoid such defects.(10)

Due to the high alloy content of such steels, outgassing of volatile compounds occurs naturally and sufficient time is required before solidification to allow these gas bubbles to reach the surface or they will be entrapped as porosity. Proper shielding of the molten weld puddle with inert gas is also mandatory to minimize defects(11) and slag formation on the surface of the weld, which can reduce penetration and facilitate porosity formation by interfering with the welding arc, as illustrated in Figure 3.(12) This figure of a G.T.A. tube weld cross-section demonstrates how arc interference creates an unsymmetrical weld metal profile that contains a shoulder area where solidification occurs more rapidly. Thus, gas bubbles are more likely to be entrapped in such a location first. Another source of arc and shielding gas interference is drafts in the vicinity of the welding torch. This and nearby strong magnetic fields can deflect the arc and cause the same effect on the weld profile, and thus incidence of porosity, as does the formation of electrically resistive slag patches.

In another study of G.T.A. welded Type 304 tubing, it was found that cracked center cavities were encountered as the travel speed was increased.(13) These are located at the centerline of the weld and are open to the surface. These defects are thought to be caused by the shrinkage that occurs as the weld metal solidifies. At slower speeds, newly melted steel, as the torch moves on, can fill these voids. Increasing the fluidity of the molten weld metal via better shielding gases, such as helium rather than argon, and increasing the mixing of the weld puddle by magnetically oscillating the arc permits faster welding speeds without center cavity formation. In addition, these techniques can improve penetration and reduce severity of undercutting (Figure 1). Multiple torch techniques provide additional benefits for avoiding such defects and achieve the fastest welding speeds possible. The onset of severe undercutting is usually the limiting factor on maximum welding speed cited when all of the above techniques are employed.

As mentioned previously, the austenitic stainless steels can be sensitive to hot cracking, or solidification cracking, during welding. Careful balancing of the alloy content promotes beneficial formation of ferrite in the weld metal of many of the commodity grades. However, before this alloying technique was widely implemented, numerous weld fabrications required repairs due to this phenomenon. In a case involving autogenous (no filler) G.T.A. tube welding of Type 347 stainless steel, Armco Researchers determined that a weld cracking problem was due to hot cracking, despite the existence of 1.6% ferrite in the weld microstructure. Tests of other material forming 2.2% ferrite showed no cracking sensitivity. Also, slower welding speeds were beneficial in this instance involving a marginal quantity of ferrite to resist cracking.(14) The benefits of slower weld travel speed were also realized in a similar investigation involving marginal weld ferrite content (1- 2%) in a Type 316 weldment.(15)

In time, it was realized that certain grades required higher ferrite content than others to resist cracking. The columbium content in Type 347 was eventually found to be a detrimental contributor to this problem, thus necessitating higher-than-normal ferrite content.(16) Many of the commodity austenitic stainless steel flat rolled products are now designed to produce 2-8% ferrite in weldments.

Another potential contributor to hot cracking is inadequate gas shielding practices. The shielding gases used at the torch must be inert to the molten metal and must protect it from nitrogen, as well as oxygen, in the air. Low flow rates, excessively high flow rates that create turbulence, and strong drafts that hinder the ability of the shielding gas to protect the molten metal are all conditions that must be avoided. It has been shown that as little as 3% addition of nitrogen to the shielding gas can cause the ferrite content to drop dramatically from 8-10% to 0%. In an investigation of an autogenous G.T.A. repair weld of Type 304 stainless steel beer containers, it was found that inadequate gas shielding allowed sufficient nitrogen to alloy into the molten weld puddle to prevent ferrite formation and, thus, led to hot cracking.(17)

Although contamination of the weldment is more often a contributor to failure in service, it can also create failures during fabrication. For example, carbonaceous agents such as oils and grease in weld joints cannot only degrade corrosion resistance, but the carbon acts like nitrogen to reduce ferrite in the weld and increase the propensity to hot crack. A less well known type of contamination involves low melting point metals, such as copper and zinc. The austenitic stainless steels are susceptible to intergranular invasion by such metals when these metals become molten.(18,19) Even alloys of such metals, such as brass and bronze, are equally hazardous when molten on solid austenitic stainless steels. As contaminants, high copper or zinc-bearing deposits, are most deleterious when located on the surfaces near enough to the weld to become molten but not near enough to alloy into the molten weld puddle (Figure 1). At this weld heat-affected-zone (HAZ) site, such molten contaminants penetrate the grain boundaries intergranularly to leave short cracks, transverse to and along the weld fusion line, at the surface (Figure 4). These can generally be seen visually, but most non-destructive methods can detect the smallest such cracks.

A most interesting investigation concerned a shielded-metal-arc (SMA) weldment of Type 304 using E308 weld rod.(20) As the cracking occurred only at areas with white markings on the surface, the marker eventually became the focus of attention and it was found that the white paint contained a high quantity of zinc. Removal of such markings from the weld area precluded recurrence of the problem.

However, most of the contamination cracking problems have involved copper-bearing contaminants. Although copper contamination cracking along weldments of commodity stainless steels has been reported occasionally, much of Armco's experiences have involved the high manganese modifications, especially alloy 21-6-9 which shows particular sensitivity to copper contamination. Generally, light abrasion of copper welding fixtures or tooling in the vicinity of the weld joint is sufficient to cause cracking of the HAZ. This most often occurs with fixed weldments, such as one investigation involving production of light gage diaphragms.(21) Chromium plated copper or steel fixtures are often necessary to avoid such problems. Although less likely to occur during continuous G.T.A. tube welding, an investigation of such 21-6-9 tubing revealed that copper contamination had occurred prior to the welding station and led to cracking in the HAZ. Eventually, the source of the copper was discovered to be the steel-colored aluminum-bronze forming rolls!(22)

Despite such sensitivity, proper care has led to the successful use of such weldments for applications from aircraft hydraulic tubing to jet engine diffuser ducts.

Service Failures: Adequate knowledge of the service environment, the capabilities of the materials, and the potential effects of the various fabricating techniques is necessary to minimize the risks of service failures, especially when weldments are involved. The more common causes of such failures involving austenitic stainless steel weldments investigated by Armco researchers involved corrosion and occasionally fatigue.(23)

Fatigue: When cyclical stresses are present in a given environment, avoidance of stress risers in the design and during weld fabrication is critical to the service life. Fatigue can even occur when the part is well designed and the proper material is selected, due to stress concentration at welds with high crowns. Concave rather than convex weld bead contours are preferred and the weld should blend into the base metal. The exaggerated convex shape of the weld bead in Figure 1 illustrates this fatigue-prone condition. Typical "clam-shell" fatigue markings were noted on the fracture faces of Type 304 stainless steel hardware utilized in the processing of poultry. This failure initiated at the toe of a weld with a convex shape, creating a natural area for stress concentration.(24)

Most of the austenitic stainless steel fatigue failures investigated occurred during high temperature service due to cyclic thermal stresses. Good high temperature strength and oxidation resistance of these steels prove beneficial for elevated temperature service. However, the relatively low thermal conductivity and high coefficient of thermal expansion leads to high thermal stresses in cyclic temperature applications, especially if mated to a dissimilar steel or if heating/cooling rates vary significantly within the component.

Type 304 stainless steel is used extensively in food handling applications; one of which is for restaurant deep vat fryers. Several investigations of failures in such components revealed that the uneven heating that occurs with combustion heated fryers, compared to resistance heated fryers, causes thermal stresses that concentrate at notches, such as incompletely fused welds, welds with poor bead shape, and crevice conditions permitted by the design. Improved design of the weldments, complete penetration, and better blending of the welds into the base metal were necessary to reduce incidents of premature failure.(25,26)

Corrosion: Most of the applications for the austenitic stainless steels involve a need for corrosion resistance. Since arc welding techniques are widely used for steel fabrication, corrosion resistance of weldments becomes equally important to that of the base metals.(27,28) The more typical corrosion problems involving austenitic stainless steel weldments are of the following types:

Rust spotting due to embedded steel or iron from tooling or fixturing. Practices to prevent this include careful handling, substitution of stainless tooling for steel or iron, and more importantly, passivation after fabrication.

Passivation is a cleaning method that removes embedded iron and steel by exposing the stainless steel surfaces to warm, dilute nitric acid for an extended period.

Rusting and/or pitting due to weld scale or heat discoloration. Mechanical cleaning, such as stainless steel wire brushing or grinding after welding, followed by scrubbing with an abrasive paste or cleaning with commercially available chemical cleaners containing phosphoric acid, should prevent both these problems.

Intergranular corrosion (IGC) of the weld heat-affected-zones (HAZ). This occurs more readily in austenitic stainless steels as the carbon content increases above .030%. The heat from welding causes chromium to combine with the carbon to form carbides in the HAZ. This depletes the surrounding area of chromium, which reduces corrosion resistance along the grain boundaries. This phenomenon is known as sensitization and can be avoided with the use of low carbon grades, grades with columbium or titanium (e.g. Types 347, 321) to combine with the carbon, or by annealing the weldment.(29,30) In certain environments, this sensitized condition leads to corrosive attack of the grain boundaries, causing whole grains to be washed from the surface (Figure 5).

Stress corrosion cracking of the weldment. This can occur in austenitic stainless steel weldments in aqueous media containing chlorides when the temperature is about 160F or higher. Although not necessary for cracking to occur, sensitization can facilitate such failure. Such failures are generally catastrophic, thus care in the selection of material is critical. A common misapplication of austenitic stainless steels is for containment of hot water with even common levels of chlorides present.(31,32) Accelerated testing is often done in more aggressive media, such as magnesium chloride (Figure 6).

Pitting of the weld metal. Due to segregation effects, ferrite formation, or crevices, pitting often occurs more readily in the weld metal than the base metal. Using techniques that promote smooth weld beads and adding highly alloyed weld fillers for environments with high risk of pitting alleviate this concern.(33,34)

Crevice corrosion of weldments. This is normally a problem of weldment design. For corrosive environments, lap welds, partial penetration welds (Figure 1), and other designs that permit stagnation of the media must be avoided.(33)

Preferential attack of the weld metal. Preferential corrosion of ferrite in the weld metal usually occurs in nitric acid environments. This is normally restricted to Type 316L welds made with a matching weld filler. Balancing the composition of the weld filler so that the chromium content is at least eight times larger than the molybdenum content has proven beneficial. Also, a more highly alloyed weld filler will solve this problem.(35,36)

Thus, certain knowledge must be acquired to prevent degradation of the corrosion resistance of an austenitic stainless steel component when weld fabrication is planned. This includes the influences on corrosion resistance of the following:

1. metallurgy of the weld deposit
2. weld process and technique effects (quality and HAZ metallurgy)
3. heat tint or scale created during welding
4. type of weld joint selected.

In general, welds are less corrosion resistant than the base metals. Thus, base metals should not be selected where only marginal resistance to the expected corrodents will result. Through investigation of a failure at a pulp mill, it was found that welds of Type 304L would corrode through the wall thickness of the pipe in 2-1/2 months when exposed to 2% sulfuric acid at 100F (37C). However, no corrosion occurred in Type 316L pipe in the same application.(37)

An example of the importance of proper filler metal selection is taken from the open literature involving the use of higher alloy austenitic stainless steels in pulp bleach plants. In locations where acidified high chloride environments exist, it has been demonstrated that the use of enriched filler metals, rather than matching fillers, is beneficial due to the high potential for pitting attack.(38)

Selection of the welding method and procedures must also be done with adequate knowledge of the corrosion environment expected in service. For example, G.T.A. welding is often used for thin sheets and develops the cleanest and most defect-free weld. However, its high heat input can more easily cause sensitization of susceptible grades. In one case, it was shown that a beverage container made from Type 304 with a moderate carbon content was sensitized when welded with the G.T.A. process but not with the G.M.A./short arc mode process.(39) In an investigation of Type 304 with higher carbon, a nickel sulfate tank suffered from intergranular corrosion and stress corrosion cracking of the sensitized HAZ of the G.M.A. welds.(40)

Weld quality can influence corrosion when contour irregularities, such as undercut, excess reinforcement, and center cavities, create crevices where corrodents can accumulate due to the stagnant conditions. A Type 304 water jacket was found to rust in normal tap water at welds with incomplete penetration, but tests of full penetration welds showed no corrosion.(41) The weld crater (depression where the weld is stopped) in a circumferential pipe weld was attacked in another Type 304 investigation where preferred arc terminating techniques were not employed.(42)

Removal of weld scale and heat tint (discoloration) is good practice for corrosive applications, but this is too often overlooked when writing the welding procedures. For example, this was identified as the cause of failure in new Type 304 piping in a brewery. Except for a trial batch of beer, the pipes had not been used. Yet, extensive pitting showed in the unremoved weld heat discoloration. The suspected corrodent was chloride-bearing sanitizing solutions that may not have been completely rinsed from the area after cleaning.(43)

For corrosion applications, weld joints that minimize crevices where corrodents can concentrate are essential to maximum service life. Pitting corrosion occurred near the lap weld in a Type 304L solar heating tank, due to the stagnant conditions between the laps.(44) Another common mistake is to require or permit partial penetration welds (Figure 1) and/or stitch welds, since they provide inherent crevice sites.

Review: Due to a variety of favorable attributes, the austenitic stainless steels are easily fabricated by arc welding processes and develop excellent as-welded properties. However, to prevent degradation of the structural and corrosion resisting properties of the base metals, care must be taken in the design, materials selection, and procedures when weld fabrication is undertaken. Compared to carbon steel welding, slower travel speeds, better shielding gas coverage, avoidance of contamination, and allowance for greater distortion are necessary for these steels. In addition to the requirements of the application and welding/fabrication techniques, adequate knowledge of the metallurgical aspects of the base metals, heat-affected-zones, and weld metal on the structural and corrosion resistant properties is essential to successful arc welding of the austenitic stainless steels.

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References

1. M. J. Cieslak, et.al.; Welding Journal, January 1982, 1-s to 8-s.
2. V. P. Kujanpaa, et. al.; Welding Journal, August 1986, 203-s to 212-s.
3. T. Ogawa, et. al.; Welding Journal, March 1982, 82-s to 93-s.
4. C. D. Lundin, et. al.; Welding Journal, August 1980, 226-s to 244-s.

5. T. A. Whipple, et. al.; Welding Journal, April 1981, 72-s to 78-s
6. T. A. Siewert; Welding Journal, March 1986, 23-28.
7. D. Hauser, et. al.; Welding Journal, Feb. 1982, 37-s to 44-s.
8. R. G. Thomas; Welding Journal, March 1978, 81-s to 86-s.
9. A.I.S.I.;"Welding of Stainless Steels and Other Joining Methods," Bulletin SS803-479-25M-GP.
10. V. P. Kujanpaa; Welding Journal, Feb. 1983, 45-s to 52-s.
11. Welding Handbook, Seventh Edition, Vol. 4, "Metals and Their Weldability", AWS 1982, 76-128.
12. Unpublished Armco Work, "Type 304 Welded Tubing Formability...", J. Tack, Sept. 14, 1982
13. Unpublished Armco Work, "GTA Weld Centerline Cavities on Type 304 Tubing...", J. Tack, July 23, 1984.
14. Unpublished Armco Work, "Weldability of Type 347...", R. Espy, May 16, 1963.
15. Unpublished Armco Work, "Examination...316 Welded Tubing", R. Espy, Sept. 23, 1975.
16. G. E. Linnert; Welding Research Council Bulletin No. 43. October 1958.
17. Armco correspondence with customer, Tack, November 15, 1984.
18. R. K. Holbert, et. al.; Welding Journal, August 1987, 38-44.
19. C. Heiple, et. al.; Materials Science and Engineering, 52, 1982, 277-289.
20. Unpublished Armco Work, "Cracking...304...Sheet", R. Larrimore, April 22, 1955.
21. Armco correspondence with customer, Espy, Sep. 5, 1968.
22. Armco internal letter, Tack to Straub, Sept. 4, 1979.
23. G. E. Linnert; Paper presented at 3rd Midwest Welding Conference, January 30, 1957, Chicago.
24. Unpublished Armco Work, "Fatigue Failure...Poultry...", K. Crooks, Dec. 1971.

25. Unpublished Armco Work, "Examination of Failed Type 302 Stainless Steel Heat...", H. Gephardt, Sept. 5, 1962.

26. Unpublished Armco Work, "Failure Analysis of Type 304 Fry Pots...", J. Tack, Oct. 28, 1985.

27. F. C. Brautigam; "Welding Practices that Minimize Corrosion," Chemical Engineering. Feb. 14, 1977.

28. A. Garner; Corrosion/78, Paper No. 20.

29. C. L. Briant, et. al.; Corrosion-NACE, Vol. 38, #9, Sept. 1982, 469-477.

30. R. A. Mulford, et. al.; Corrosion-NACE, Vol. 39, #4, April 1983, 132-143.

31. G. E. Moller; Materials Performance, May 1977, 32-43.

32. T. P. Hoar, et. al.; Journal of the Iron and Steel Institute, Feb. 1956, 124-143.

33. A. Garner; Metal Progress, April 1985, 31-36.

34. G. E. Hale; Research Report, The Welding Institute, 250/1984, Oct. 1984.

35. A. Garner; Metal Progress, April 1985, p 31.

36. R. H. Espy; Paper presented at Midwest Welding Conference, January 29, 1964, Chicago.

37. Unpublished Armco Work, "Weld Seam Corrosion...Sulfuric Acid", K. Crooks, Mar. 10, 1976.

38. A. Garder; Welding Journal, Sept. 1986, 39-44.

39. Unpublished Armco Work, "Pickling Attack of Weld HAZ in Type 304 Beer Barrels...", J. Tack, Sept. 26, 1983.

40. Unpublished Armco Work, "Corrosion...Nickel Sulfate Solution", R. Espy, Nov. 17, 1954.

41. Unpublished Armco Work, "Type 304 Water Jacket Corrosion...", J. Tack, Nov. 30, 1982.

42. Unpublished Armco Work, "Pitted Type 304 Tubing...", J. Tack, Aug. 11, 1983.

43. Unpublished Armco Work, "Pitting of Type 304 Brewery Pipe Elbow", J. Tack, Jan. 18, 1983.

44. Unpublished Armco Work, "Corrosion of Type 304L Solar Heating Tanks...", R. Gaugh, July 18, 1983.

Figure 1
Butt Weld, Transverse Cross-Section

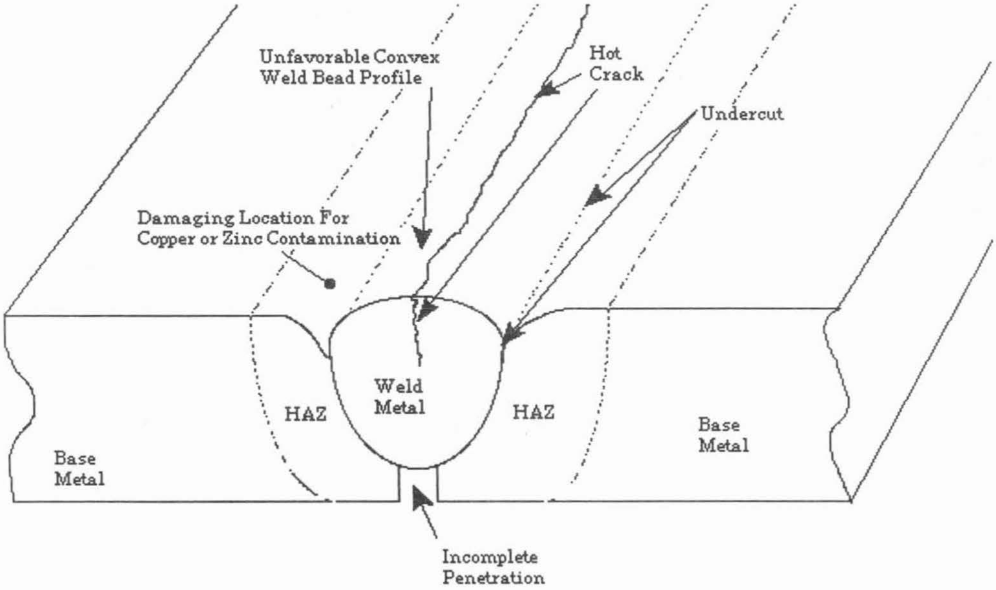


Figure 2

G.T.A. Weld Data On .08" Thick 316[10]

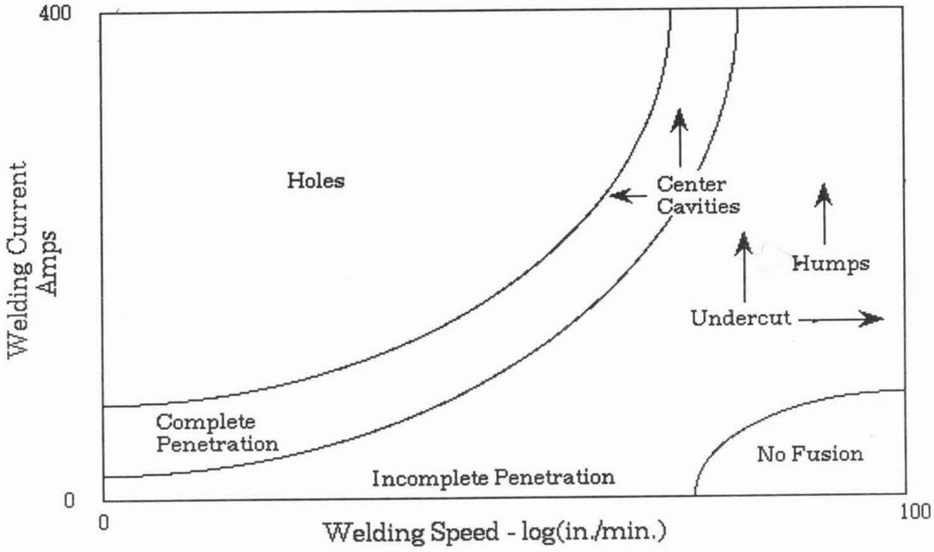


Figure 3
G.T.A. Tube Weld
Transverse Weld Cross-Section
Arc Interference

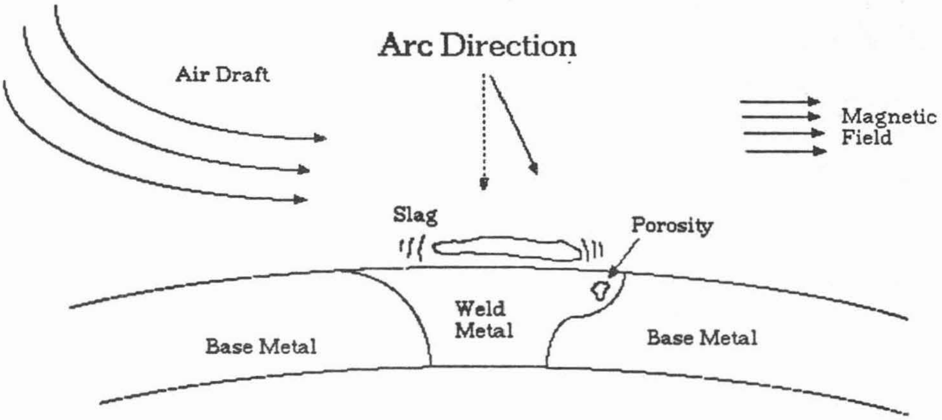
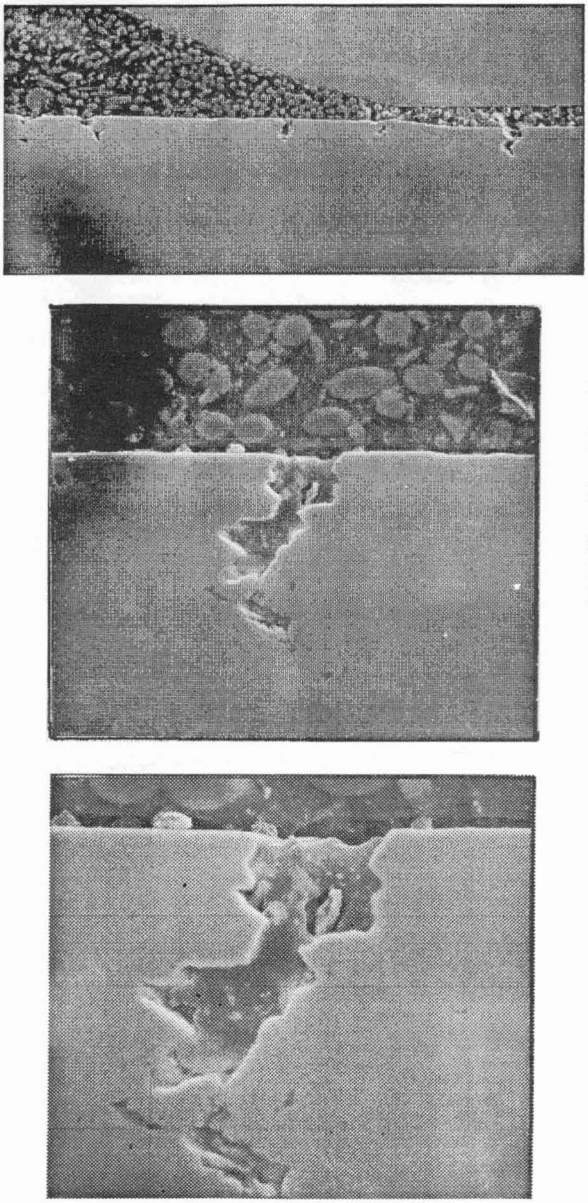


FIGURE 4

As Polished
Longitudinal
S.E.M. 100X/500X/1000X



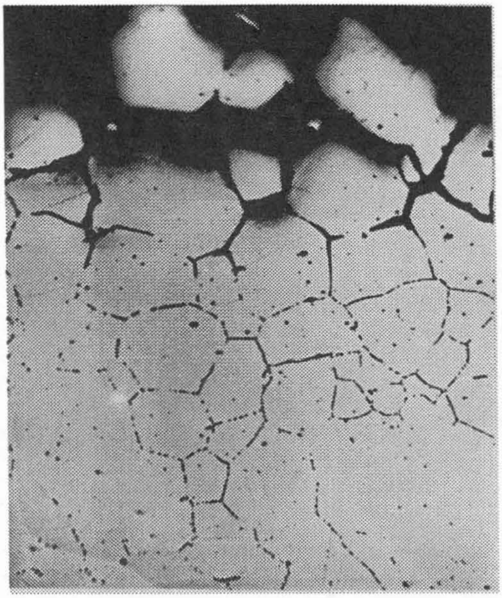
21-6-9 Molten Copper

Penetration At G.T.A.

Heat-Affected-Zone (HAZ):

Scanning Electron Microscope Photomicrographs at Increasing Magnification.

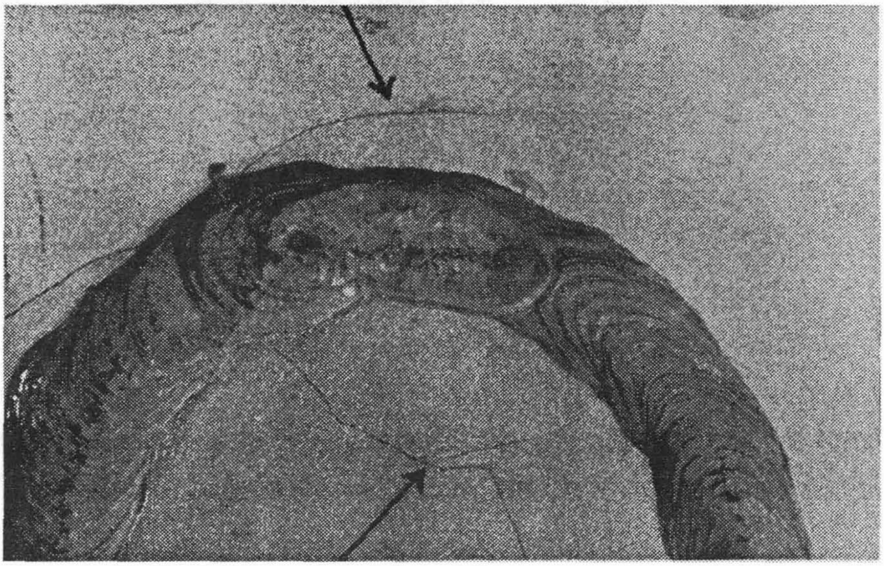
FIGURE 5



Intergranular Corrosion of Sensitized Zone in Type 304 Stainless Steel. Attack Via Grain Boundaries Containing Precipitated Carbides Detaches Whole Grains From Surface.

Etchant: Electrolytic NaCN Mag. 250X

FIGURE 6



Weldment of Type 304L Stainless Steel Which was Exposed in As-Welded Condition to a Boiling Magnesium Chloride Solution. Stress-Corrosion Cracking in Base Metal Indicated by Arrows.

Mag. 2X