FABRICATION PROBLEMS AND FAILURES IN VESSELS AND PIPING IN AMMONIA AND RELATED PLANTS

Severe service placed on materials in these plants increases possibilities for failure but proper quality control and planning can help reduce the frequency.

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Metal products involving vessels and piping generally are the same regardless of the process application in which they are used. Nevertheless, plants producing ammonia, methanol, and related products appear to have been particularly susceptible to service failures.

Many failures are due to a combination of the relatively severe service conditions involved with inherent weaknesses and internal defects in the materials. As in other types of chemical plants, petroleum refineries, and power plants, these failures are usually ascribed to one or several of the following classifications: (1)

1. *Design:* Structural (flexibility), design notches, joint locations, or joint configurations.
2. *Materials:* Selection and handling of base and welding materials.
3. *Base metal defects:* Introduced by the manufacturer of the plate, pipe, casting, forging, fitting, etc.
4. *Fabrication:* Fabrication and erection of pressure vessels or piping components, welding, heat treatment, etc.
5. *Service:* Excessively severe service conditions—overheating, overpressure, thermal fatigue, etc.

Choice of materials

Modern ammonia, methanol, and related plants utilizing steam reforming processes are operated at temperature of 1,400 to 1,700°F., and even higher. Although materials are available for service at these and still higher temperatures, economic considerations require the specification of more conventional materials. Most commonly used are stainless steels of the 25 Cr - 20 Ni and 15 Cr - 35 Ni types, or modifications thereof.

These materials can perform satisfactorily at the elevated temperatures to which they are subjected. For maximum assurance of satisfactory performance, however, closer than normal attention must be given to chemical compositions, defect limitations (homogeneity), design, fabrication, heat treatment, and welding.

Quality control aspects appear to be particularly deficient in the materials, components and fabrication and welding operations involved in the manufactured and erected equipment, pressure vessels and piping systems.

It is also rather surprising how little one industry frequently has learned from the problems and experiences of another industry, even though the piping and pressure vessel materials used are the same in industries involved in power production (utilities), gas transmission, missiles, petrochemical plant, or fertilizer production operations. Thus one industry rarely utilizes the experiences of another industry in the writing of realistic specifications covering materials, fabrication, welding, heat treatment, and quality control.

Homogeneity factors

Although rolled, extruded or forged pipe products tend to have a more homogeneous metallurgical structure than castings, the cast products generally are so much more economical that their prohibition may be very difficult to justify.

Among the various types of defects in castings, shrinkage is the one considered most critical and potentially hazardous.

Figure 1 illustrates cracking in the crotch area of a series of cast tees installed in a methanol furnace. A closeup is shown in Figure 2. The castings are made of HK-30 alloy (25 Cr - 20 Ni stainless steel with about 0.35% C). At the ends, the outside diameter is 6¼ in. and the wall thickness is 0.63 in. In the crotch where the cracking is apparent, the wall thickness is 0.56 in.

Cross sectioning through a typical crack, Figure 3, shows that the cracking is the result of shrinkage which formed during solidification, Figure 4. In the as-cast condition, the cracks did not actually penetrate to the surface, so that their presence was not detected by visual and liquid penetrant examination of the surface. However, after the circumferential butt welds had been made between the cast tees, the resulting normal residual welding stress was sufficient to propogate the cracking from the end of the shrinkage within the casting to the surface.

Similar critical defect conditions can occur also in wrought plate and pipe materials and in forgings. The apparent lamination, shown in Figure 5 in Incoloy pipe, actually represents severe cracking which occurred during the extruding operation, Figure 6. Although these cracks frequently occur parallel to the surface, and thus may be of minor consequence, they occasionally occur angular to the surface, thus reducing the effective wall thickness of the material, and representing conditions susceptible to crack propagation during service.

Severe surface slivers and ruptures in plate and pipe are illustrated in Figure 7. Although they are frequently minor, they may penetrate to levels significantly below the minimum wall thickness and thus can be critical. To avoid subsequent ruptures during service, the extent of such surface defects must be explored. In the severe example illustrated in Figure 7, the material should actually have been rejected.

Chemical composition

Careful attention must be given to chemical compositions. Slight variations, even within the limits permissible in the applicable materials standards, may result in problems during fabrication or lead to service failures.

In some stainless steel grades, silicon in increasing amounts tends to promote fissuring. This has been recognized in weld deposits for many years, Figure 8 (2). As discussed subsequently,

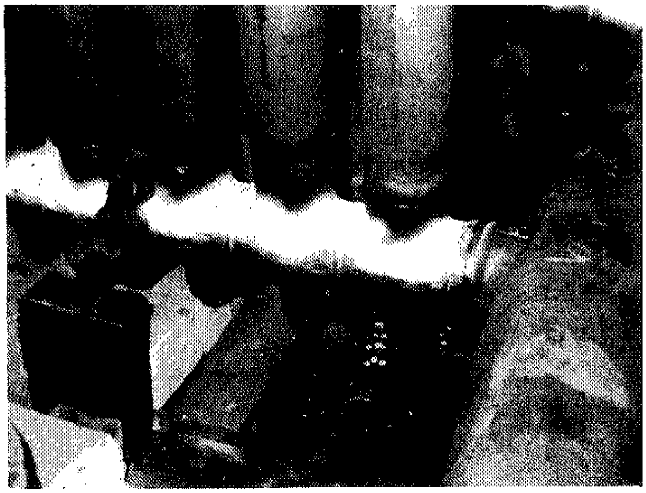


Figure 1. Cracking in crotch of HK-30 stainless steel tees in methanol steam reformer furnace.

Figure 2. Closeup of typical cracks revealed by liquid penetrant examination.

silicon may also tend to promote fissuring in castings.

In 25 Cr - 20 Ni weld deposits, a higher carbon content (of over 0.30%) may be desirable to inhibit sigma phase embrittlement.

Metallurgical hot shortness

A major problem with most of the stainless steels, and with some of the high-nickel alloys utilized in steam reformers, involves their extreme susceptibility to hot shortness.

Hot shortness defined as "brittleness in hot metal" is generally related to films of impurities and nonmetallic materials which are present in grain boundaries. In certain temperature ranges, they reduce significantly the cohesive strength (hot ductility) of the material. The tendency towards hot shortness is greatest just below the melting point. In many austenitic stainless steels, this tendency continues to temperatures as low as 1,400°F.

Hot shortness frequently is most severe when the impurities, nonmetallic inclusions and metal phases are concentrated along the grain boundaries and become liquid at temperatures below the melting point of the alloy. This is commonly referred to as liquation.

In HK and similar type stainless steel castings, silicon is one of the major elements tending to cause hot shortness. An example

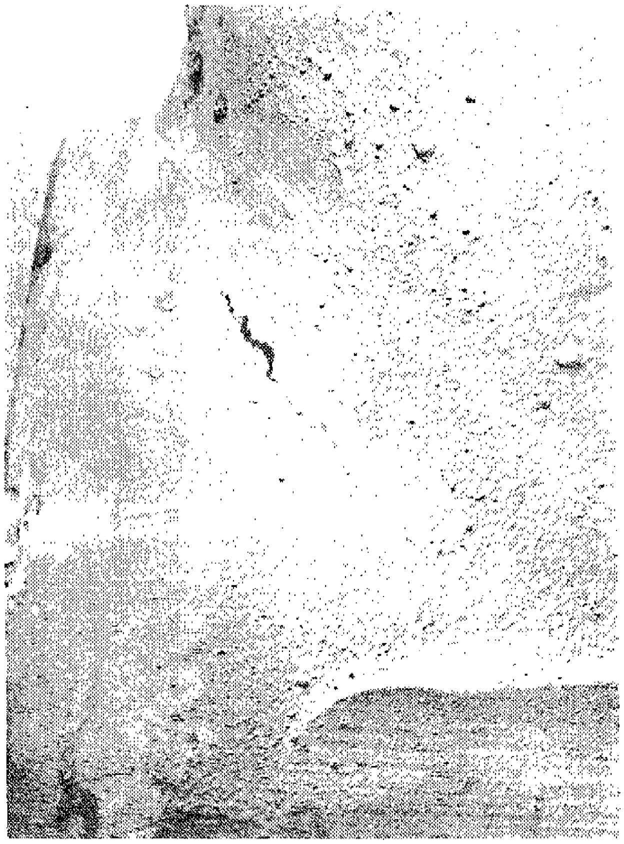


Figure 3. Typical tight crack prior to cross sectioning.

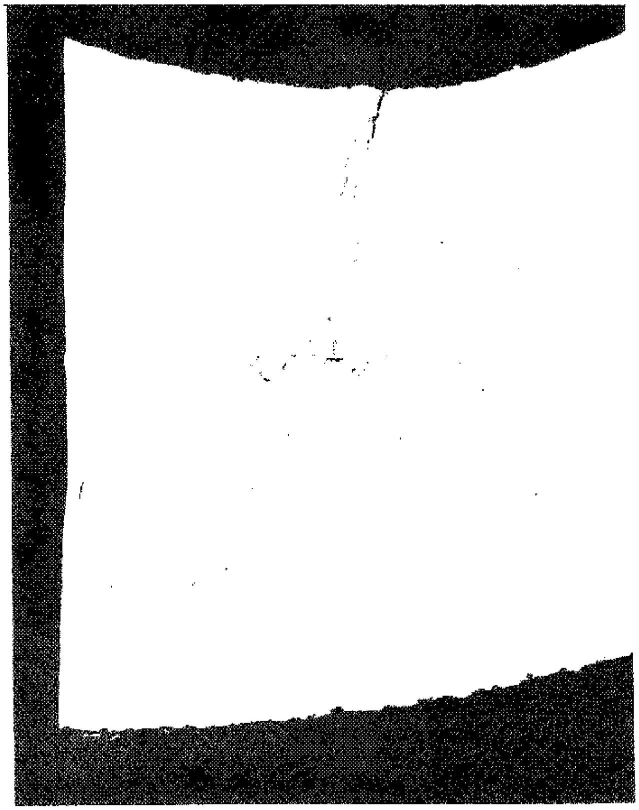


Figure 4. Cross section through crack shown in Figure 3, to illustrate extent and depth of shrinkage.

Figure 5. Cross section through extruded Incoloy pipe material indicating lamellar-type defect.

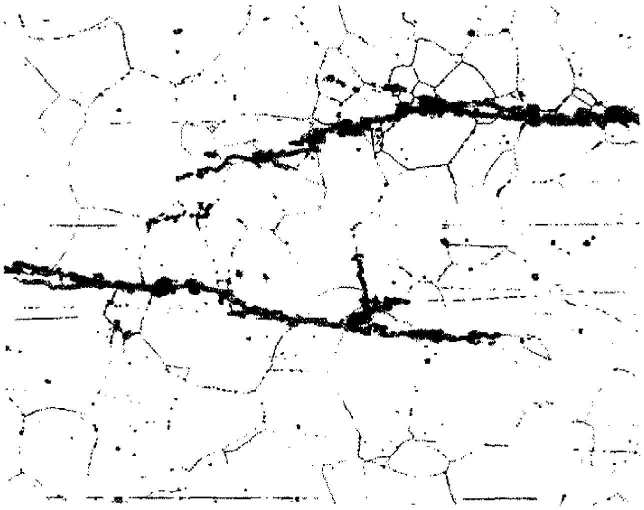


Figure 6. Magnification of defect confirming that it represents cracking.

of severe hot shortness in a 15-in. O.D. by 2-in. wall cast elbow is shown in Figure 9. The severe intergranular fissuring occurred in the "as-cast" condition.

Although the tendency towards this fissuring tends to increase when the silicon content is increased from 1% to 1½%, many other factors are also involved. Thus, some HK-30 castings with silicon contents as low as 0.75% have exhibited severe hot fissuring in the as-cast condition; other HK-30 castings with 1.5% silicon have been sound. Excessive purity of the melt, as produced by induction melting with "all-virgin" alloy constituents, can produce a far greater susceptibility than the use of a 50% virgin metal - 50% scrap mixture melted in an arc furnace.

Where a casting does exhibit severe fissuring due to hot shortness, very little is gained by a weld repair in the foundry. Such castings should be considered extremely hot short and rejectable.

Although the as-cast, as-forged, or as-extruded products may appear free of fissures, the material may nevertheless be hot short and develop severe fissuring in the weld heat affected zone during subsequent welding. An example of this is shown in Figure 10.

Figure 7. Photograph of stainless steel plate surface showing presence of severe slivers, laps, and ruptures.

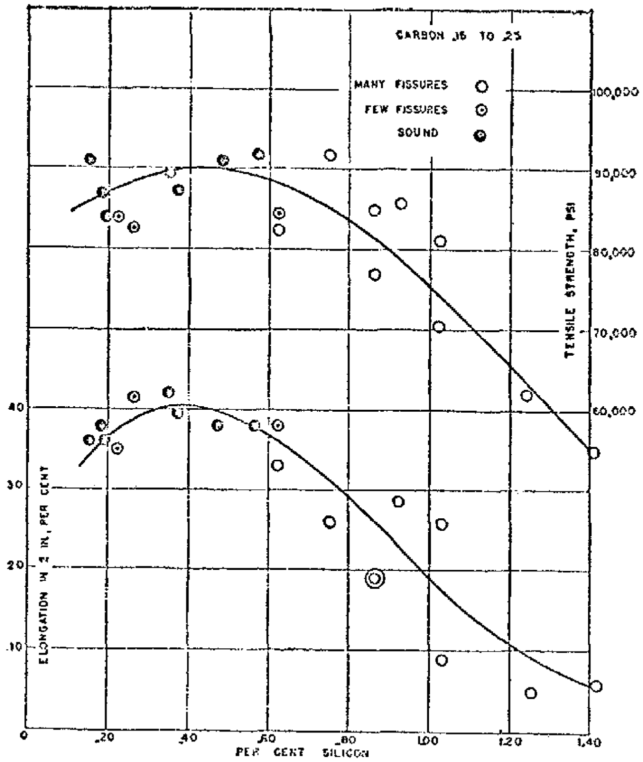


Figure 8. Effect of silicon upon tendency to fissure and on mechanical properties of 15 Cr.-35 Ni. stainless steel weld deposits (2).

Figure 9. Photograph of 15 in. OD HK-30 stainless steel elbow (half-section) with severe hot fissuring apparent after penetrant inspection and deep etching, which also revealed large grain size.

Where severe hot cracking occurs adjacent to a major pressure-bearing weld, the service life may be significantly reduced. In joints experiencing minor service loadings, such as in some nozzle joints, this hot fissuring may not be critical and result in a service failure, Figure 9.

Weld metal cracking

One of the major conditions leading to cracking is the inherent hot shortness in the base metal, already discussed, or in the welding filler metal. To minimize hot fissuring in weld deposits, particularly those of the 25 Cr - 20 Ni compositions, the welding filler metals now used normally contain only 0.50 to 0.75% silicon. Where the 15 Cr - 35 Ni grades are welded with Inconel 82 and 182 filler metals, weld metal cracking as a result of hot shortness is not a common problem.

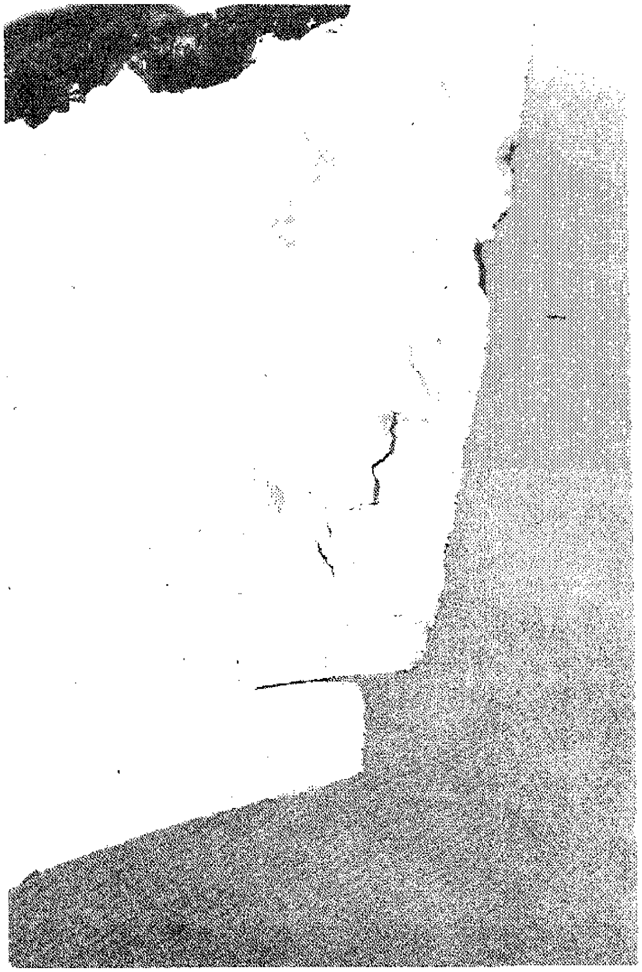
Even though a casting, forging or wrought pipe or plate material may not evidence cracking in the as-cast or forged condition, the material may nevertheless, be inherently hot short and crack during welding. The welding stresses cause cracking in the heat affected zone along the grain boundaries of the base metal as a result of the low cohesive strength at elevated temperatures above 1,400°F. Examples are shown in Figure 11.

In the higher carbon stainless steel castings such as HK-40, particularly when the grain size is coarse, the presence of significant grain boundry carbides may also cause cracking during welding. This cracking occurs near room temperature where the carbides are brittle and tend to rupture as a result of welding stresses.

Even where a material is not hot short, cracking may occur as a result of severe welding stresses. As the weld cools and shrinks, the stress across the weld increases. Since the cohesive strength near room temperature generally is lower in the base metal than in the weld deposit, cracking may occur in the base metal. An example is shown in Figure 12. Adjacent multiple weld repairs caused the particularly severe stress, which led to the crack. The crack path is sketched in Figure 13. The cracking did not penetrate into the weld overlay on the inside of the centrifugally cast tube.

Other causes of cracking

Welding stresses can also open up dross-type base metal inclusions which may occur as intergranular films, particularly along the inside surface in centrifugally cast tube. Examples of the cracking and of dross inclusions are shown in Figures 14 and 15. To avoid this, some companies specify that the centrifugally cast



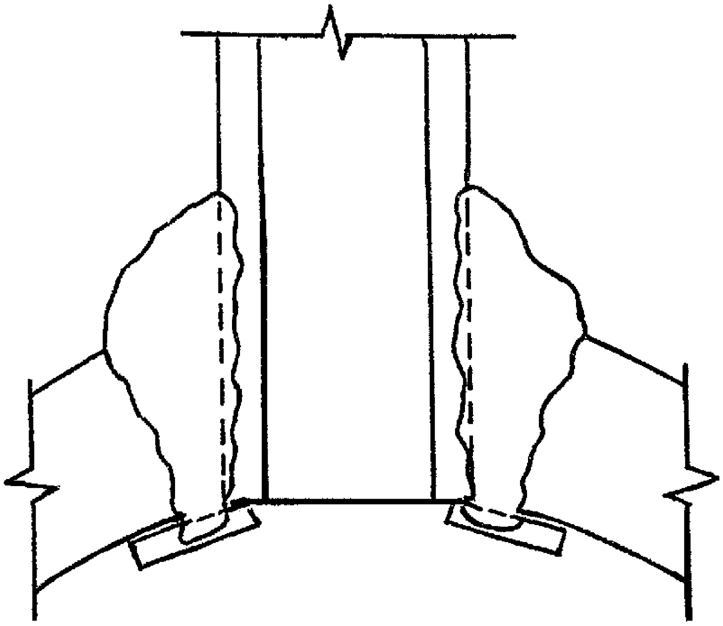


Figure 10. Cross section of nozzle weld into 5-in. dia. by 1/¼ +IN. WALL HK-30 stainless steel tube with severe hot fissuring present in 1½-in. nominal dia, cast stainless steel nozzle section. After 2 yr. of service at 1,550°F, an actual failure had not developed in this nozzle section.

tubes for reformer applications be internally bored.

Finally, cracking in the weld itself may occur as a result of weld shrinkage. Potentially, centerline shrinkage cracks, as shown in Figure 16, are of greatest concern.

Although most problems have been encountered in high-temperature applications involving stainless steels and high nickel alloys, cracking problems can be encountered even at room temperatures in carbon or low alloy steel materials.

Figure 17 shows an ammonia tank, 42 in. in dia. by ⅜-in. wall, where an initial crack occurred across the seam weld after approximately 1½ years of service. The crack was repaired but within a few months, a second crack was apparent on the surface. This was repaired, but was followed by a third, and later on, a fourth crack. Radiographs of the weld seam revealed two additional transverse cracks in the development stage, but not yet apparent since they had not reached the outside surface of the vessel, Figure 18.

The seam weld had been made by automatic submerged-arc welding. It was not stress relieved, as this was not a requirement of the applicable codes. Nevertheless, cracking would not have occurred if the weld had been stress relieved.

Because of the many different conditions which can lead to cracking, different remedies are necessary. Where hot shortness is the principal cause, preheating should not be done and the interpass temperature should be kept as low as possible, preferably below 250°F. On the other hand, where the presence of intergranular carbides causes cracking, a preheat and interpass temperature at 300°F. will keep the metal more ductile and minimize cracking. Where stresses are the primary cause, as on the illustration shown in Figure 12, an interpass temperature of 500°F. will reduce the weld shrinkage and the resulting stresses.

Welding filler metal selection and welding process details are also very important factors which should be considered. For example, 25 Cr - 20 Ni stainless steel filler metals with a carbon content of less than 0.20%, has resulted in cracking, particularly in the root of the weld.

Effect of processes and techniques

Where service requirements involve temperatures between 830 and 1,150wF., chromium-molybdenum alloy steels are frequently used. Where those have been welded with stainless steel filler metals, such as 25 Cr - 20 Ni, or 18 Cr - 8 Ni compositions, and the service involves thermal fatigue conditions, cracking may occur, Figure 19. Careful attention, therefore, must be given to the proper selection of the welding filler metal. The welding filler metals should be of compositions as similar as possible to those of the base metals involved.

It must also be recognized that different welding processes may have different tendencies towards producing weld defects. Where the base metal contains a significant level of nonmetallic inclusion, the cracking tendency is far greater in weld deposits made by inert-gas tungsten-arc welding, than in welds made by shielded metal-arc welding with flux-coated electrodes.

The shorting-arc type gas-shielded metal-arc welding processes may produce weld deposits with substantial lack of fusion between weld deposits, Figure 20. Such defects are not likely in weld deposits made by the shielded metal-arc welding and by the submerged-arc welding processes. A number of service failures in ammonia plant equipment has been due to the presence of severe lack of fusion in weld joints made by the shorting-arc welding processes.

Expensive equipment has been ruined and costly interruptions in plant operations have been the result of extremely careless welding techniques.

Very sloppy welding of the butt joint on the inlet of a high pressure valve resulted in substantial burn-through and the retention of unfused insert ring material. During service, part of the unfused insert ring broke off. The insert ring sections, and broken-off weld metal particles which entered the valve severely damaged the valve seats and plugs, Figure 21, and in time made the valve inoperative. Aside from ruining a valve worth several tenths of thousands of dollars, plant operations were interrupted.

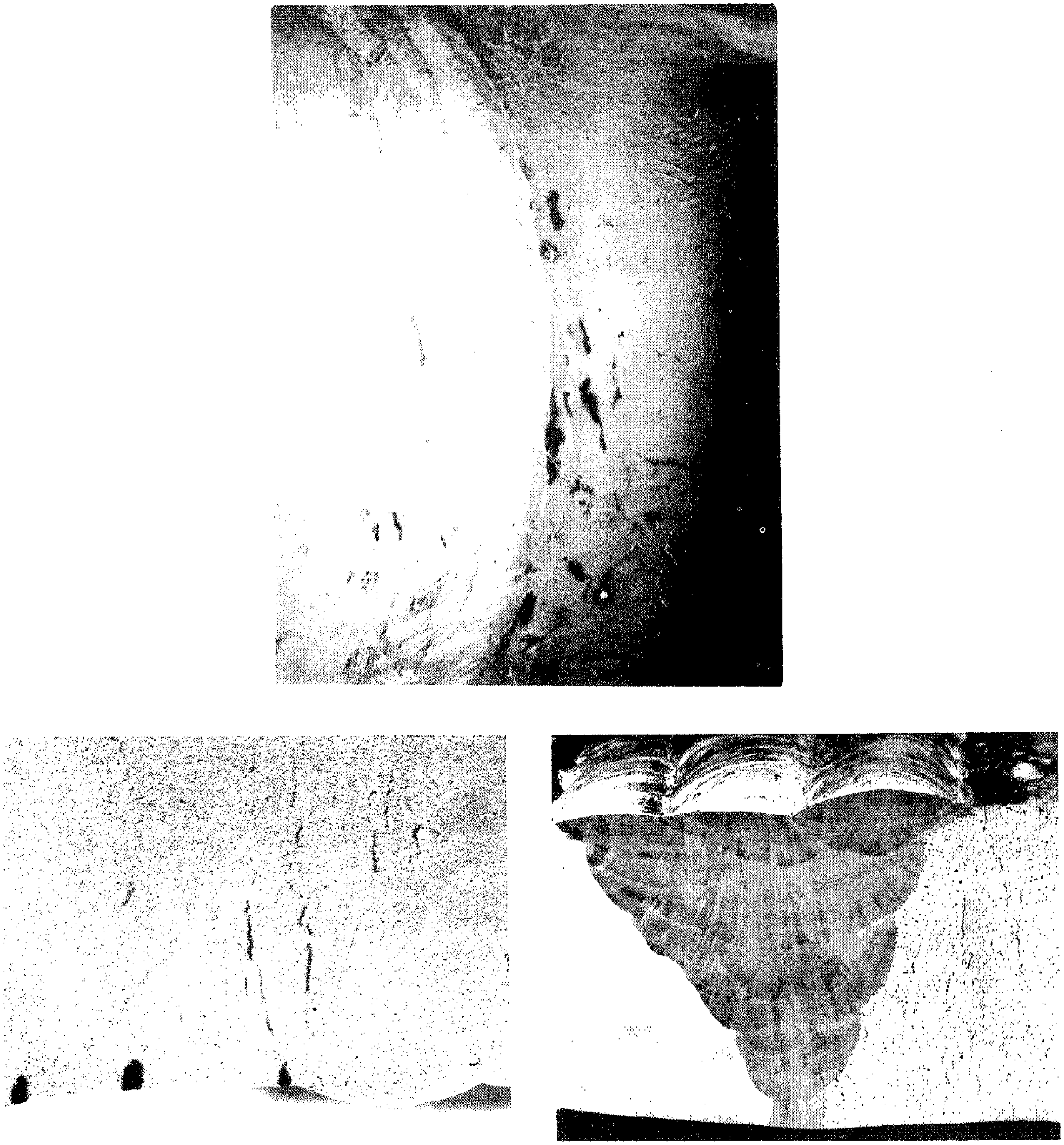


Figure 11. Severe hot fissuring adjacent to weld in HK-30 5-in. dia. by ¾-in. wall stainless steel fitting.

Service failures and embrittlement

Service failures can generally be related to: (1) Serious defects present in the original component or weld, (2) metallurgical deterioration occurring at the elevated temperatures involved, or (3) mechanical stresses or mechanical fatigue, or thermal fatigue or shock.

The most common cause of metallurgical embrittlement is caused by sigma-phase formation. In certain austenitic stainless steels, this highly brittle phase forms during long-time elevated temperature service between 1,050 and 1,700°F. The presence of considerable quantities of the sigma phase tends to result in a serious loss of toughness at room temperature with notch impact toughness valves becoming less than 1 ft.-lb. Figure 22 shows cracking across a 5-in. diameter by ½-in. wall reformer tube of centrifugally cast HK 30 stainless steel.

An increase in the service temperatures of the hot ammonia synthesis gas to 600°F. led to hydrogen embrittlement, blistering, and rupture in 8-in.Sched.80 carbon steel pipe, Figure 23. At these temperatures, chromium-molybdenum steel piping only are considered adequate.

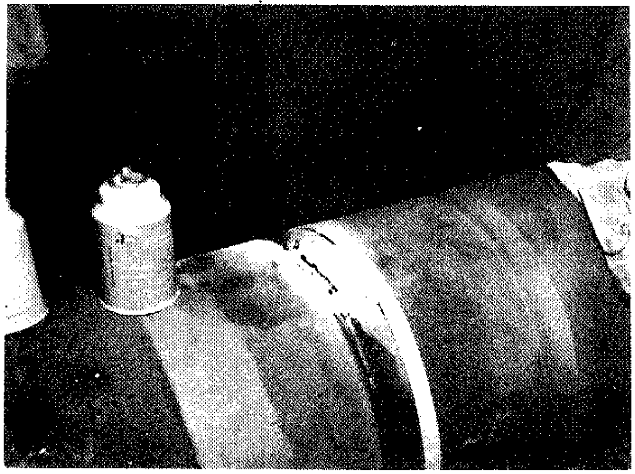


Figure 12. Cracking along weld edge caused by excessive welding stresses when welding without preheat. (Pipe diameter 15 in. by 1¼-in. wall).

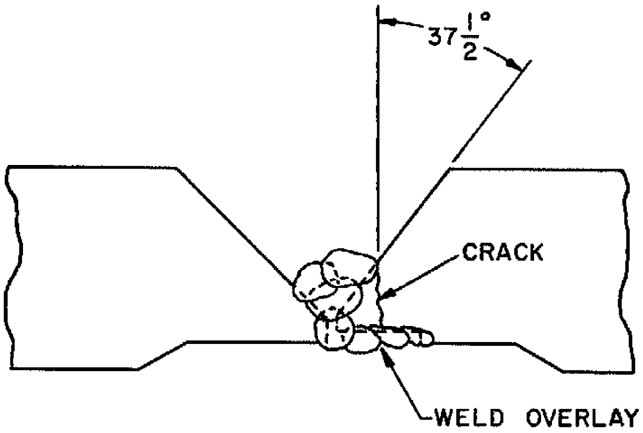


Figure 13. Sketch illustrating crack path through HK-30 base metal and stopping at weld overlay.

Mechanical or thermal stresses

Severe movement of furnace elements as a result of design deficiencies or operational conditions can cause high stress levels in nozzles and other branch connections. An example of cracking in a ring header system related to bending moments caused by header rotation is shown in Figures 24 and 25.

Failures in quench tanks and in the piping leading to the quench tanks generally are the result of thermal fatigue, Figure 26. In these components, particularly close attention must be directed towards design and fabrication to minimize the severity of the thermal shock on the metal and to avoid notch conditions.

Cracking in the cone section of a nitric acid converter made of ⅝-in. thick Type 405 stainless steel is illustrated in Figure 27. Intermittent water and steam quenching of the surface normally at 1,600°F. was considered the primary cause. The extent of cracking by thermal fatigue is further illustrated in the radiographic film shown in Figure 28.

General comments

Numerous other examples could be cited of fabrication problems leading to failures. (1, 3)

It must be recognized in a limited report such as this, that the isolated examples given do not imply that a particular product, material form, or alloy is more prone to failure than another not illustrated. Instead, these examples, as well as those cited by others, must be broadly projected and carefully interpreted.

Not enough can be said for careful and realistic quality control

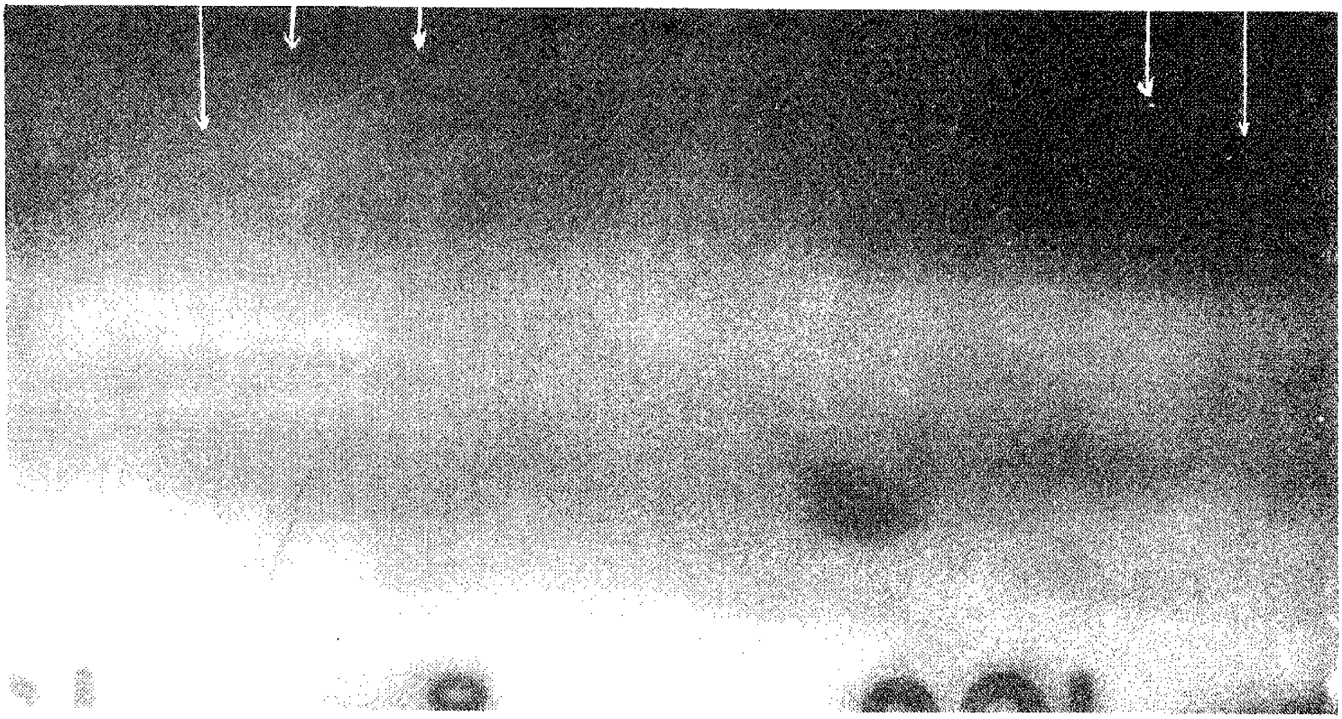


Figure 14. Radiograph showing cracking in centrifugally cast HK-30 stainless steel pipe caused by widening of dross inclusions. (Crack locations indicated by arrows).

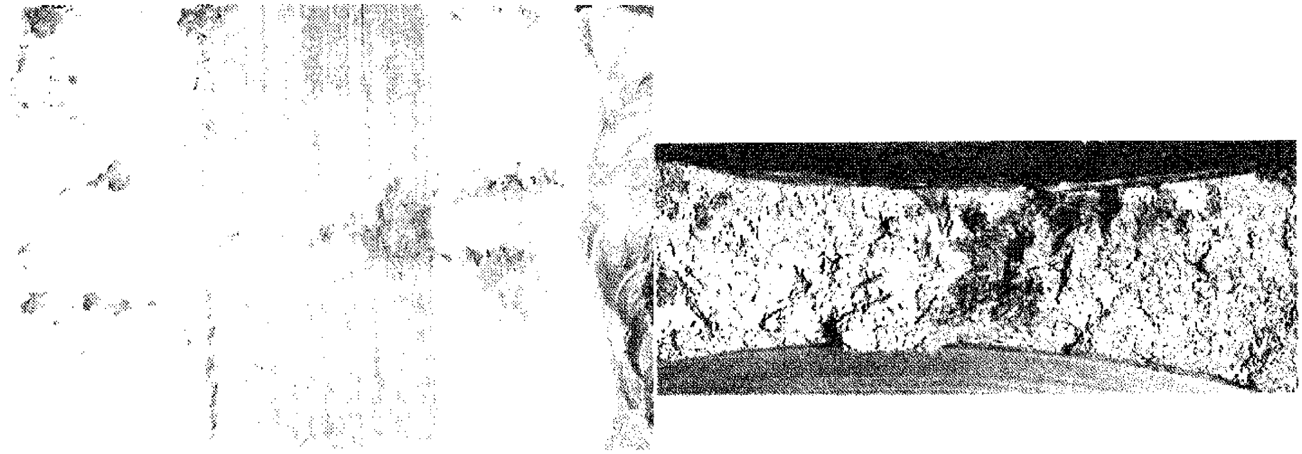


Figure 15. Examples of dross inclusions apparent on inside pipe surface and on fracture surface of centrifugally cast HK-30 stainless steel pipe.

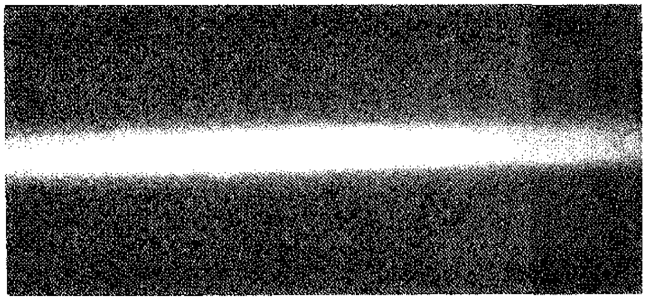


Figure 16. Radiograph showing centerline shrinkage in center of butt weld.

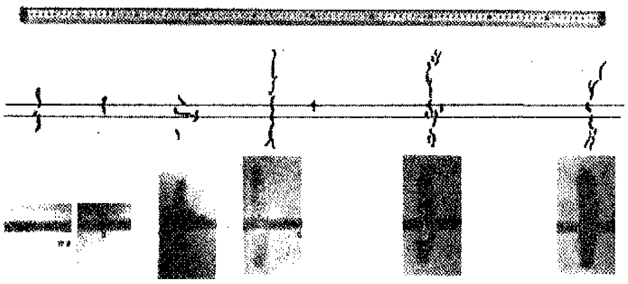


Figure 18. Sketch of seam weld with prints of radiographic film to illustrate cracking and weld repairs in 42-in. dia. ammonia tank.

Figure 17. Side of 42-in. dia. carbon steel ammonia tank with welds 10½-in. apart representing cracks which had propogated across ⅜-in. vessel wall after 1½ to 2 yr. of service.

over all materials, manufactured plate and piping products, and fabrication and welding operations. (4) Too often, an inconsequential weld defect such as porosity, which is readily detected on a radiographic film, is repaired, only to be replaced by a critical defect such as a crack which is not readily detected by radiographic examination. (4)

Proper planning and preparation of specifications and manufacturing, fabrication and erection procedures is essential to provide maximum assurance of sound equipment and plants. Just as important will be the constant exercise of experienced technical judgment in solving specific problems which arise during the fabrication, welding, heat treatment, and erection operations.

The same considerations should apply to the repair of failed components and systems. Too often, remedies are prescribed by long distance, without actual examination of the failure by a qualified and experienced engineer fully familiar with the metallurgical conditions, the effects of welding, and the limitations of nondestructive inspection. Sometimes, changes in the repair procedure or additional operations are advisable in order to insure that the weldment has optimum soundness.

Many repairs made without proper supervision and judgement are prone to fail more quickly than the original weld. For example, overemphasis of between-pass grinding in repair welds may cause severe distortion, stresses, and cracking. The results of careful analyses of the causes of a failure must be utilized in prescribing proper repair procedures. This must include also recognition of any metallurgical changes, deterioration, and stresses which may have occurred as a result of the previous service of the components involved.

It is also important to recognize that nondestructive testing may provide a false sense of security, particularly when the inspection procedures have not been carefully detailed and the results have not been properly interpreted.

Just because one product from a manufacturer is sound does not mean that another is. There have been many instances, for example, where stainless steel elbows from a foundry were sound, while cast valves shipped from the same foundry and assembled, contained leaks in a pressure test. Both product runs had been subject to routine radiographic foundry quality control inspection.

Failures can also be avoided by routine inspection and spot checking of materials, equipment and weld joints with a history of failure problems.

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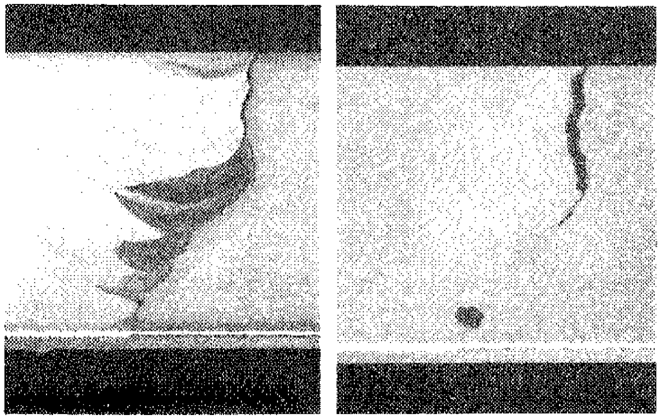


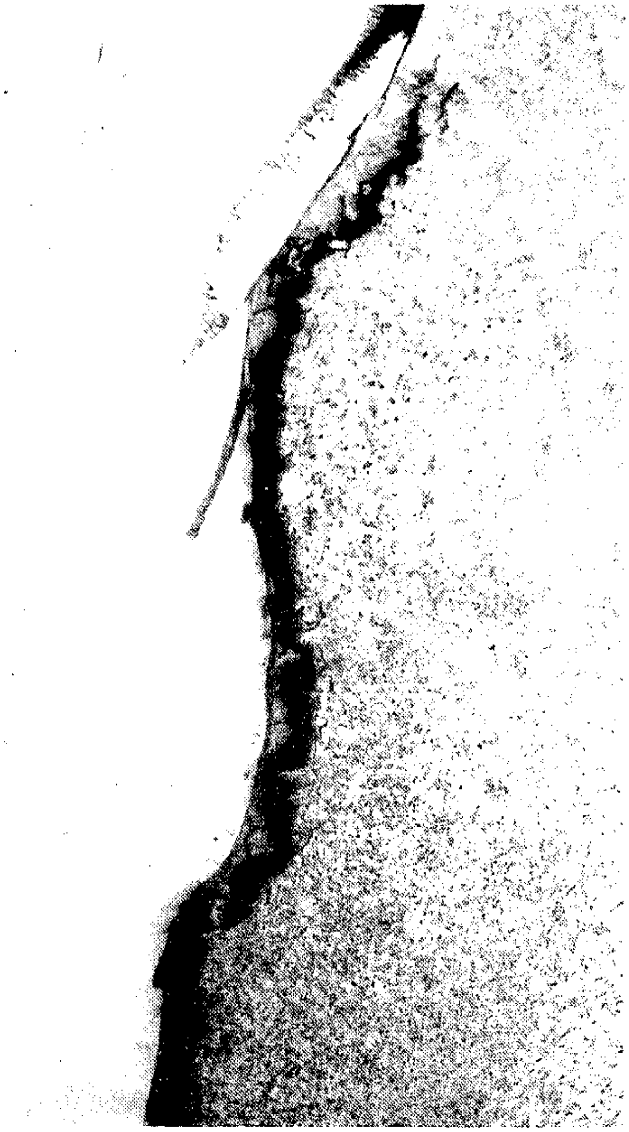


Figure 19. Cross section of pipe weld involving 18 cr - 8 Ni 2 Mo stainless weld deposit on 2½ Cr-1 Mo alloy steel. Crack delineated by liquid penetrant inspection. Photomicrograph shows that crack propogation occurs along weld edge.

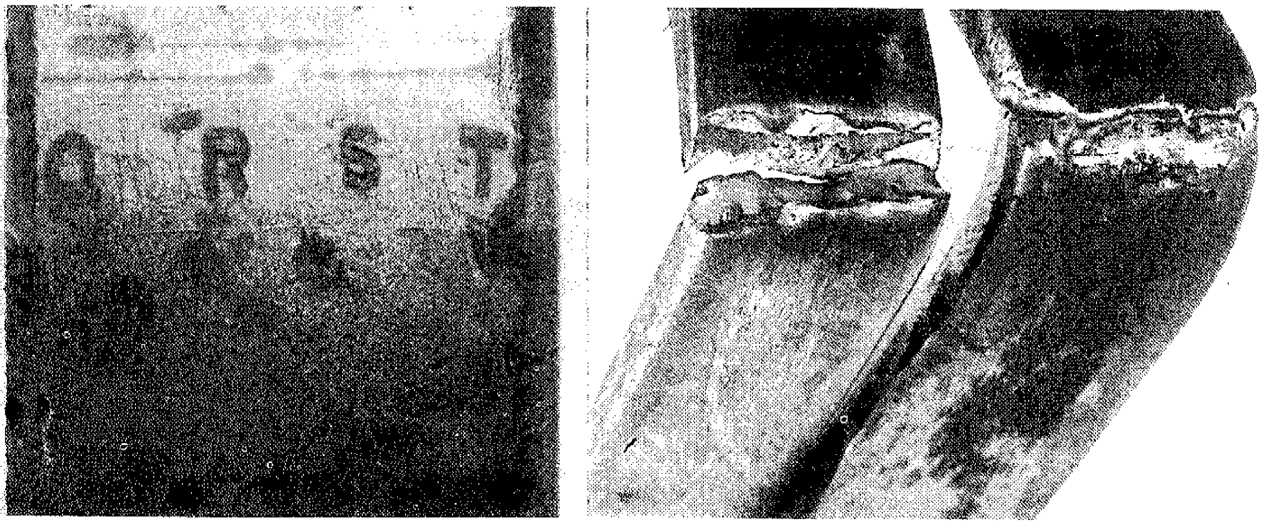
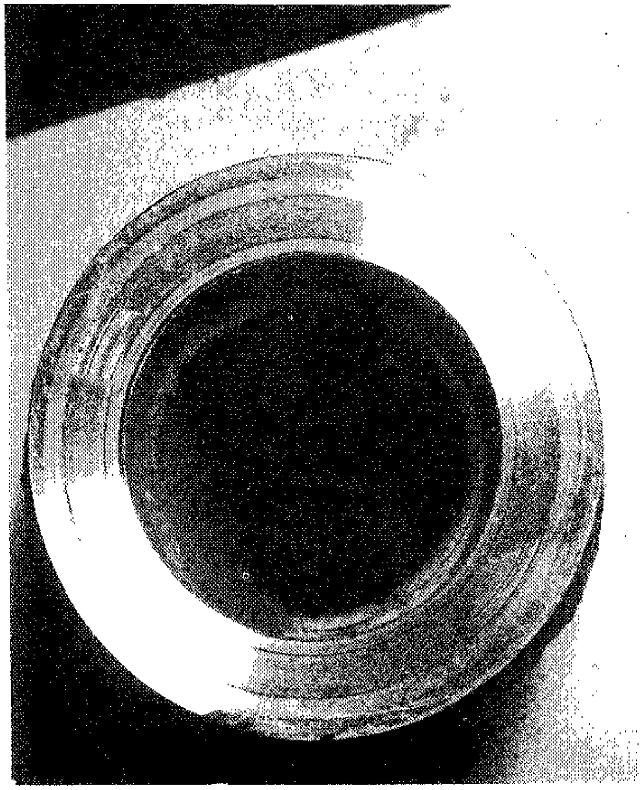
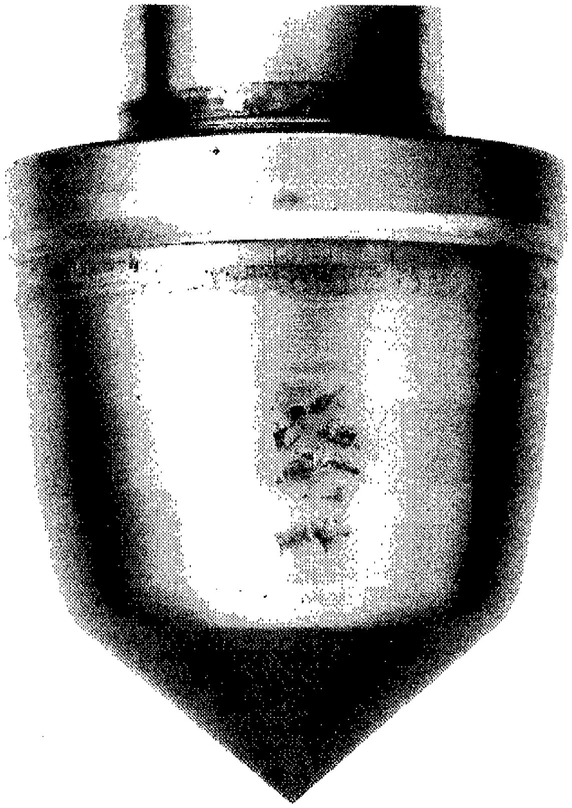


Figure 20. Lack of fusion between weld deposits made with the short arc welding process. Fractured A.S.M.E. code bend test specimens confirm severe lack of fusion.



(A)



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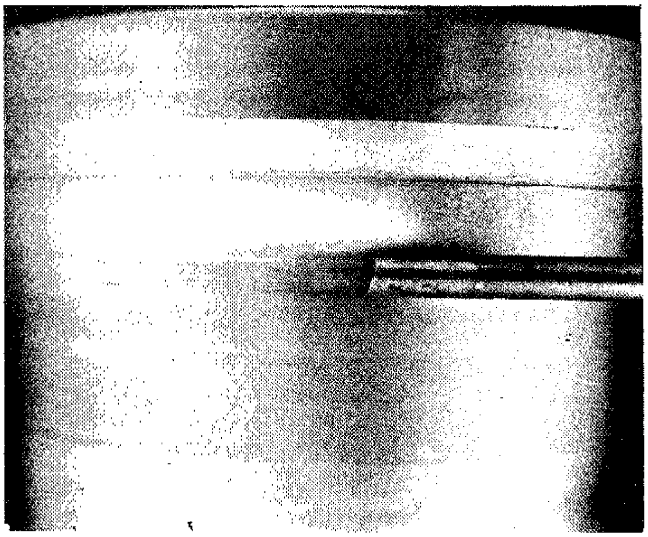

(C)

Figure 21. Damage to stainless steel valve plug caused by improper erection welding. (A) Shows severe burn-through and unfused consumable insert ring, with broken-off section of unfused ring missing. (B) Shows severe scoring of valve plug cuased by loose particles, and (C) relates scoring on valve plug to loose section of consumable insert ring.

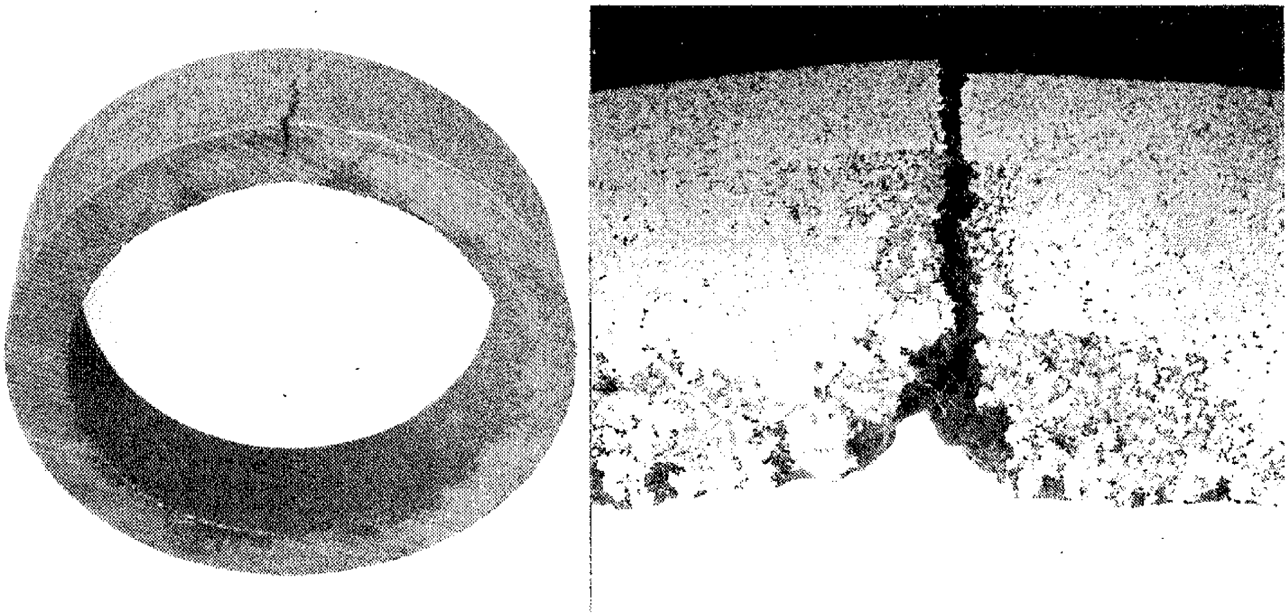

Figure 22. Cracking in 5-in. dia. by ½-in. wall HK-30 stainless steel reformer tube, caused by sigma phase formation. Failure occurred after 10 yr. of service at 1,340°F.

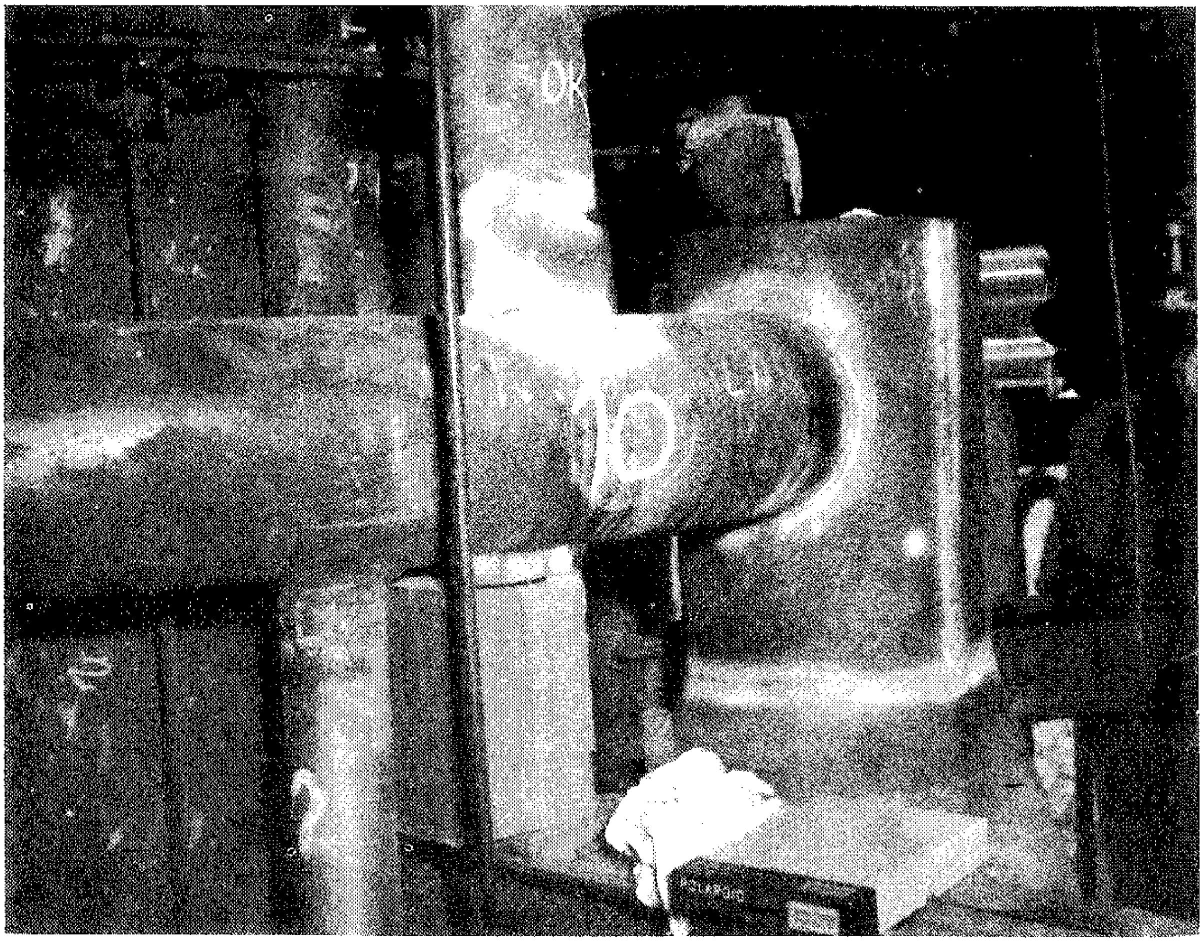

Figure 23. Example of cracking in nozzle welds in Incoloy ring header.

Figure 24. Cracking inside reformer furnace in elbow to vertical pipe weld caused by rotation of ring header below furnace wall.

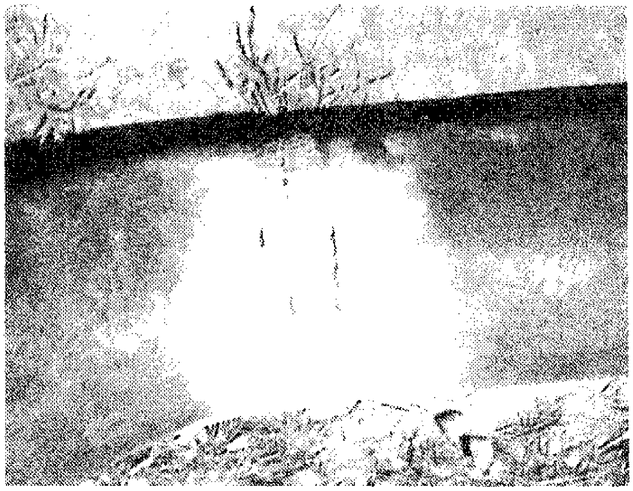

Figure 25. Thermal fatigue cracking in Type 316 stainless steel pipe weld in pipe section connected to quench tank.

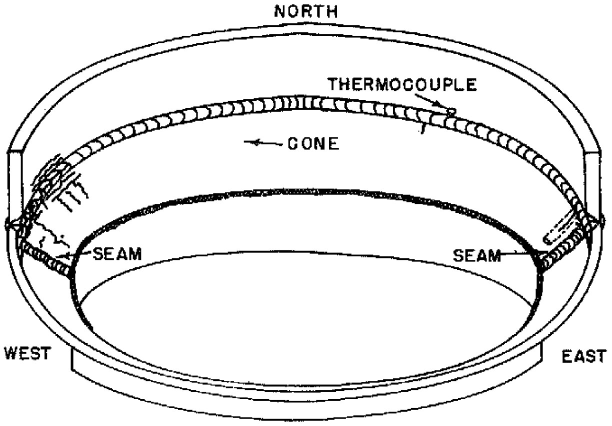

Figure 26. Sketch illustrating cracking in nitric acid converter cone section made of Type 405 stainless steel.

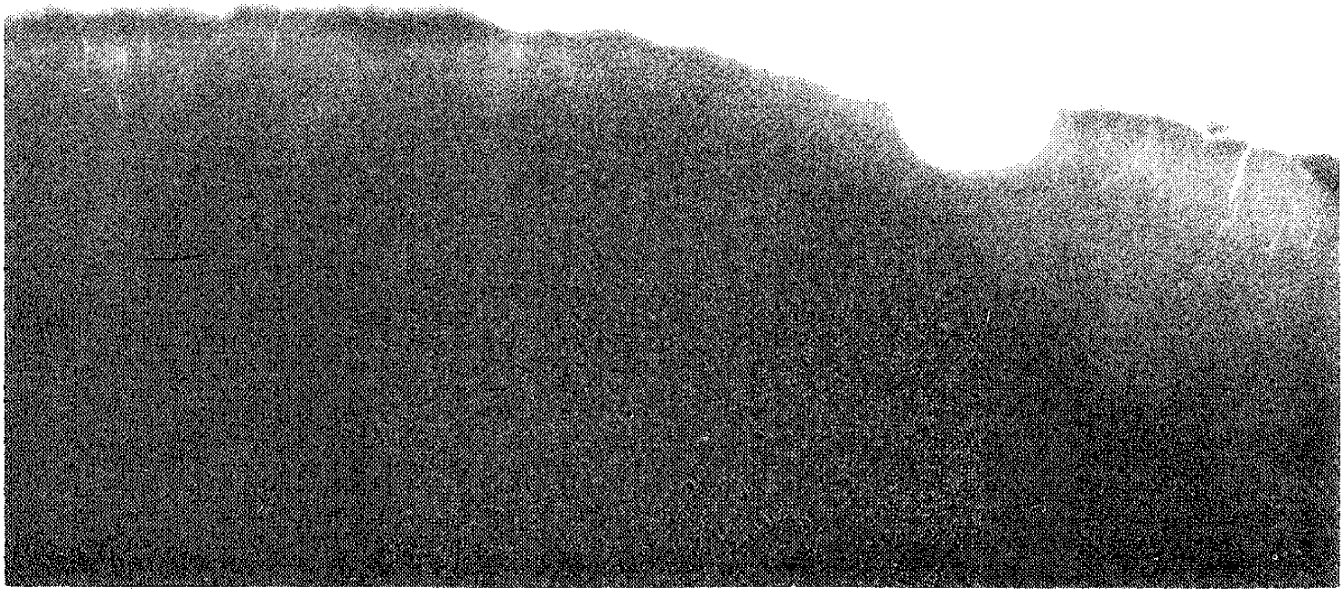

Figure 27. Radiograph showing extent of cracking in cone section.

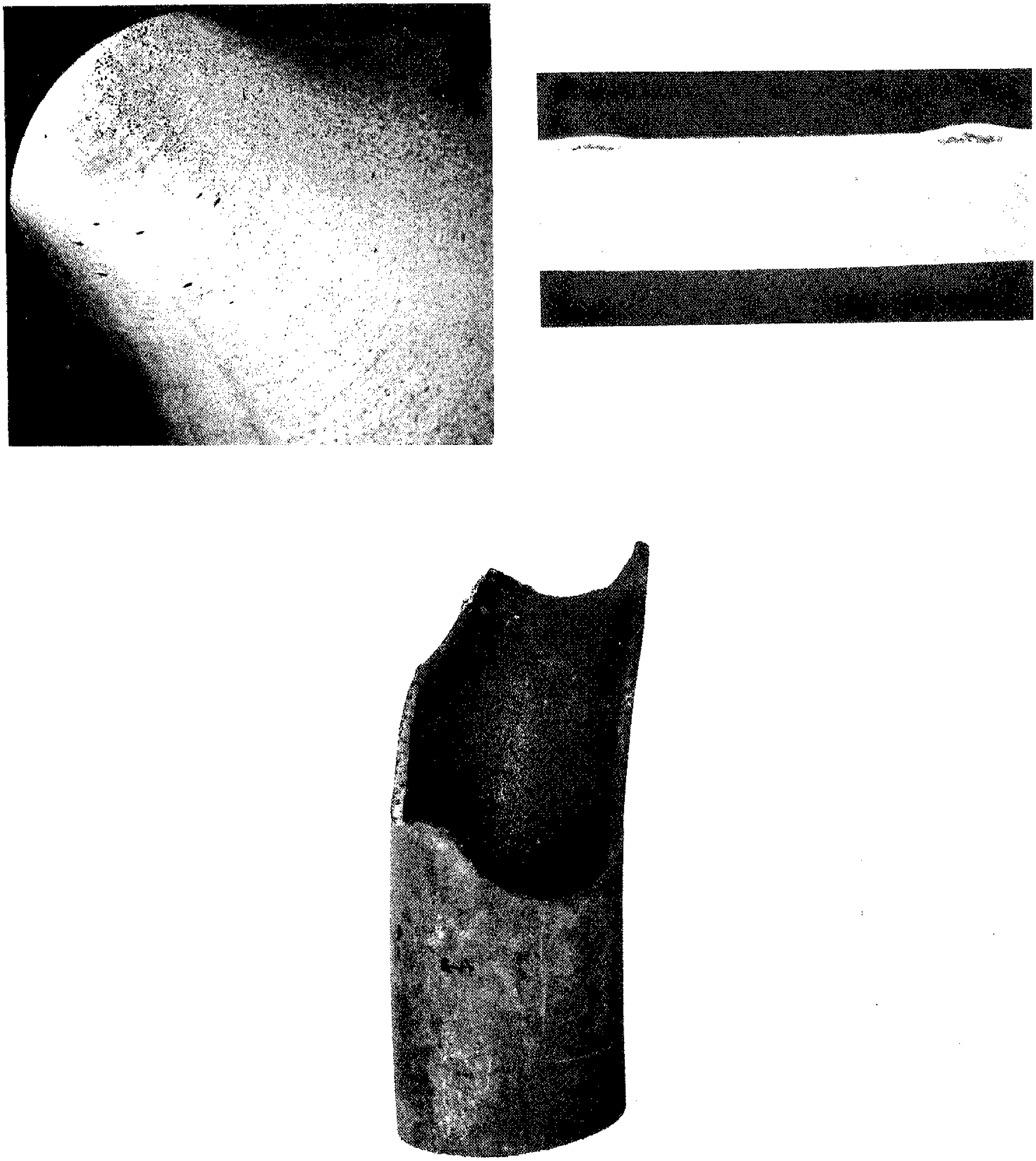

Figure 28. Rupture, blistering, and hydrogen embrittlement in 8-in. Schedule 80 carbon steel pipe.