# High-Temperature Piping Systems for Petrochemical Processing

**Investigations of recent failures involving Incoloy alloy 800 in the pigtail piping of reformers have brought out important points to consider in designing and fabricating high-temperature piping systems.**

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In the past year, a number of failures involving Incoloy nickel-iron-chromium alloy 800 have occurred in the pigtail piping of reformers used in the production of ammonia synthesis gas.

The operating temperatures and pressures of reformers have recently increased. Although these increases have contributed to some failures, investigations made to determine the causes of other failures have brought out some additional important points to consider in designing and fabricating high-temperature piping systems.

## Base material

In general, the basic qualities required in a construction material for high-temperature petrochemical processing are resistance to oxidation, sulfidation, carburization, and corrosion and adequate mechanical strength, thermal fatigue strength, and stress-rupture properties at the involved temperatures. In addition, the material must be weldable and formable.

Incoloy alloy 800 fulfills all of the requirements. However, the alloy must be used in the correct condition and fabricated by the proper techniques to obtain maximum service life under the conditions imposed by reformer applications.

Because of the high temperatures involved (above 1,100°F), the design stresses for construction materials are normally based on creep and rupture strength. Insufficient stress-rupture strength is the most common cause of pigtail piping failure.

Failure analyses performed in six cases of pigtail piping failure have shown that the material was in the wrong condition and consequently had low stress-rupture strength. Alloy 800 pipe is produced in three tempers: mill-annealed, solution-annealed, and as-extruded. The as-extruded temper is the equivalent of solution-annealed temper since the extrusion process is performed at solution-annealing temperatures. To have maximum stress-rupture strength, the alloy must be in the solution-annealed or as-extruded condition.

Pipe in sizes used for pigtail piping (usually 1¼ or 1½-in. pipe size with a Schedule 40 or 80 wall) is normally produced as cold-drawn, mill-annealed material. If the design stresses are based on the creep and rupture strength of solution-annealed material, the pipe obviously must be solution-annealed before being put into service. In the six failures mentioned previously, it was found that the material had not been properly heat-treated. Laboratory examination of the material indicated that the maximum temperature to which it had been exposed was approximately 1,900°F. This constitutes a mill anneal; a minimum of 2,000°F is required to solution-anneal alloy 800.

In the case of fabricated pigtail piping, it must be decided whether to solution-anneal before or after forming. This decision depends on the amount of cold work involved in forming and the maximum service temperature to which the piping will be exposed.

## Effect of cold work on properties

If pigtail piping is solution-annealed before forming, either at the mill or by the fabricator, the effect of cold working on stress-rupture properties must be determined.

Laboratory tests have indicated that cold working in amounts of up to 25% has no adverse effect on the stress-rupture strength of alloy 800 at temperatures of up to its recrystallization point. The stress-rupture properties of cold-worked material are shown in Table 1.

Cold working does, however, lower the recrystallization temperature of the metal and also affects the amount of grain growth that will occur during a subsequent heat treatment. Table 2 shows the results of some rupture tests performed on cold-worked alloy 800. The grain size of the rupture test specimens indicates that the recrystallization temperature of solution-annealed material that has been cold-worked 25% is between 1,400 and 1,600°F and is probably above 1,550°F. Such material could therefore be used at temperatures lower than 1,550°F with no loss of stress-rupture strength. For use at higher temperatures, the material must be re-solution-annealed after forming.

Approximately 10% cold work, in the form of bending, is required to fabricate pigtail piping. Material cold-worked to this degree has a recrystallization temperature of about 1,725°F. However, it should be remembered that recrystallization temperatures are approximations and that it is impossible to operate a unit at precise temperatures. Consequently, a safety factor must be employed in determining design stresses and operating temperatures. It is recommended that pigtail piping be solution-annealed after forming if the service temperature is above 1,500°F, even though the recrystallization

**Table 1. Rupture life of cold-worked Incoloy alloy 800 (material solution-annealed prior to cold work and tested at 1,500°F and 8,800 lb./sq. in.)**

| Cold strain, % | Rupture life, hr. |
|---|---|
| 0 | 41.9 |
| 2 | 41.6 |
| 10 | 130.3 |
| 25 | 175.6 |

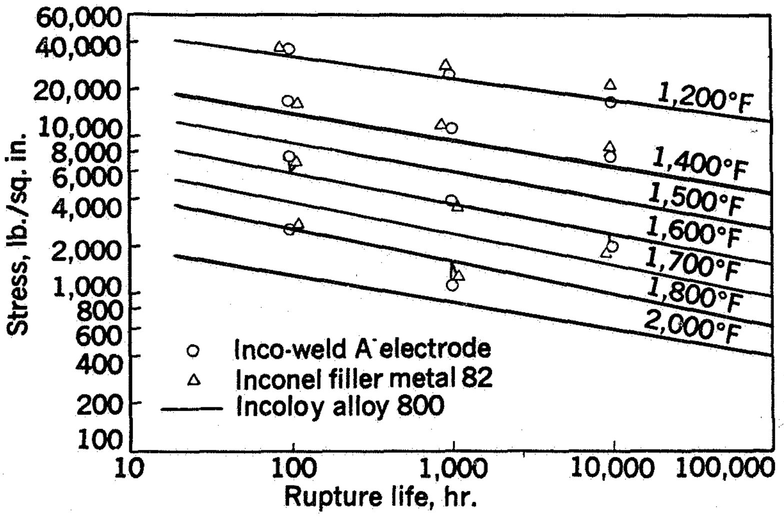

**Figure 1. Stress-rupture strengths of weld metals and solution-annealed or extruded Incoloy alloy 800.**

temperature of the metal is 1,725°F.

### Verifying properties

The first step in ensuring that the material will have the desired properties is to make certain that it is of the correct composition. This is best accomplished by purchasing material to a society (ASTM, ASME, etc.) specification. The variations in chemical composition permitted by these specifications are not sufficient to cause significant differences in properties.

At temperatures above 1,300°F, solution-annealed material has a stress-rupture life of approximately double that of mill-annealed material. It is important, therefore, to determine that piping, as put into service, is in the solution-annealed condition. This can be done by several methods.

The most reliable method to determine the true condition of the material is a rupture test performed at the operating temperature of the unit. A rupture test which duplicates service conditions is impractical, because reformer units are designed for a life of 10 yr. or longer. However, rupture tests performed at the actual service temperature but at increased stress offer practical and reliable means for determining the material's condition.

Another test that can be used as an indication of the condition of the material is grain size determination. This method is not as reliable as the stress-rupture test but is more economical and requires less time.

No cases have been reported in which alloy 800 having a grain size of ASTM No. 5 (0.0025-in. average diameter) or coarser did not have the stress-rupture properties of solution-annealed material. However, in some instances, material having fine grain has also had high stress-rupture strength. Material asserted to have been properly solution-annealed and still having fine grain can be checked by the stress-rupture test previously discussed.

### Weld metal

Many of the criteria used in selecting the base material are also used in judging the suitability of the weld metal for high-temperature petrochemical applications. However, in addition to high-temperature strength and corrosion resistance, factors such as operability, joint design, ease of slag removal, and design of the fabricated unit must be considered in selecting the weld metal and the process by which it is applied.

### Stress-rupture properties

The stress-rupture strengths of welding materials commonly used to join Incoloy alloy 800 piping (Inconel filler metal 82 and Inco-weld A electrode) are shown in Figure 1. In general, these welding materials have stress-rupture strengths greater than Incoloy alloy 800 at the temperatures encountered in petrochemical processes.

Wrought materials such as alloy 800 exhibit good stress-rupture ductility over a wide temperature range. Weld metals, however, usually have lower stress-rupture ductility than their wrought equivalents. Welds of stainless steel and Inconel alloy compositions often exhibit stress-rupture ductility as low as 5% or less.

The low stress-rupture ductility of weld metals must be recognized in designing high-temperature piping systems. Units should be designed so that welds are placed in locations where the effects of low stress-rupture ductility will not be detrimental. Generally, this involves placing the welds in areas where minimum deformation at high temperature occurs.

For example, a horizontally positioned pipe having a longitudinal weld should be turned to locate the weld at the top rather than at the bottom. If the weld is positioned at the bottom and sagging occurs during high-temperature service, the weld is forced to elongate with the wrought material. When the weld reaches its limit of stress-rupture ductility, it will develop transverse cracks and fail. Locating the weld at the top of the pipe greatly reduces the amount of weld metal elongation during sagging.

### Thermal fatigue

Weld metals are inherently lower in thermal fatigue strength than wrought materials. A high nickel content improves the thermal fatigue resistance of welds, and substituting a weld metal that contains more nickel for one of lower nickel content has been effective in increasing the service life of some welds. However, design modifications are usually necessary to gain acceptable service life for welds subjected to extreme thermal fatigue conditions.

Thermal fatigue is basically a stress problem—the stress being primarily a result of thermal gradients caused by thermal cycling. Although thermal fatigue failures may occur in simple shapes such as round bars, the tendency to fail increases as the geometry of a part becomes more complex or as the part becomes more massive.

When design modifications are made to minimize thermal fatigue failures, welds should be located in areas of low stress. Locating welds in corners and in areas where sectional size or dimensional changes occur results in the welds being at points of stress concentration. Moreover, welding defects such as undercutting, lack of penetration, weld craters, and excessive

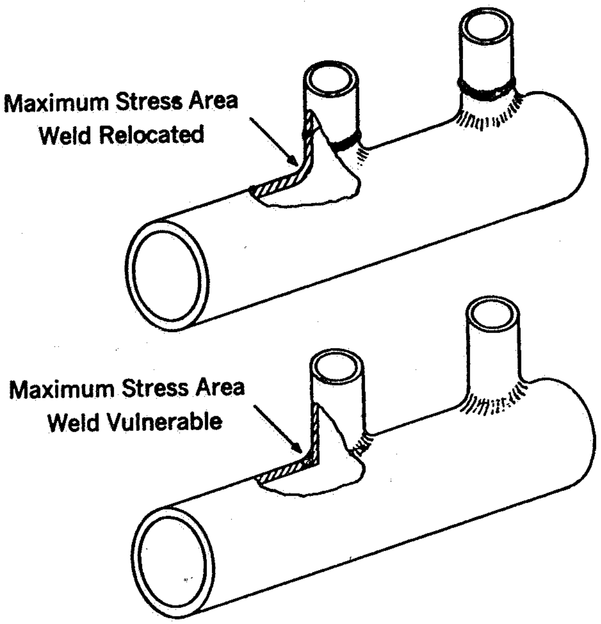

**Figure 2. Example of locating welds in areas of known low stress where thermal fatigue failures occur.**

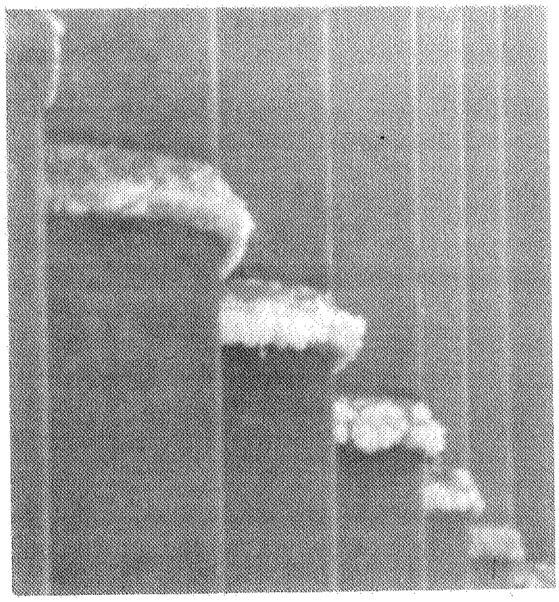

**Figure 3. Corrosion deposits around welds in furnace tubes.**

weld reinforcement further weaken welded joints.

Thermal fatigue failure of welds in quench pot sections of hydrogen reformers has been found to be caused by improper design. Figure 2 illustrates a design that is particularly prone to failure by thermal fatigue. This figure also shows a modification of this design which relocates the welded joint to a more favorable position.

## Weld slag corrosion

At high temperatures (usually above 1,300°F) and under certain atmospheric conditions, slag deposited by covered welding electrodes causes severe corrosion. In oxidizing environments, the slag becomes increasingly fluid and aggressively attacks the metal (*1*). In reducing atmospheres, the weld slag continually absorbs any sulfur that is present and causes sulfidation of the base metal.

Several years ago, at an East Coast oil refinery, sulfur accumulated in weld slag caused failure of the furnace tubes in a hydrogen reformer (*2*). Incoloy alloy 800 furnace tubes were welded with Inco-weld A electrode. During the first month of service, the sulfur content of the furnace atmosphere was not closely controlled and reached concentrations of up to 260 gr./100 cu. ft. Crusty corrosion deposits (Figure 3) formed around the welds, and the furnace tubes failed after only one month of service.

Sand blasting to remove the loose slag and corrosion deposits exposed a dense, metal-like layer. Analysis of the layer showed that 11% total sulfur was present as chromous sulfide, iron chromium sulfide, and nickel sulfide. Both the weld metal and the base metal had been attacked. The tubes were repaired by removing the high-sulfur layer and rewelding.

This failure illustrates the need to remove completely all weld slag from the outer surface of shielded metal arc welds. The slag is best removed by grinding and abrasive blasting.

The failure also illustrates the undesirability of covered electrodes for the root pass of welds that cannot be completely cleaned on the inside surface. Welds that cannot be cleaned on the root side and will be exposed to potentially corrosive environments should always be made by one of the gas-shielded arc welding processes, such as gas tungsten arc welding or gas metal arc welding.

## Carburization

Some petrochemical processes, notably those for ethylene production, tend to build up coke deposits on the inside surface of furnace tubes. Surface roughness and discontinuities on the inside of tubes accelerate coke buildup.

An internal weld root surface with excessive reinforcement, crevices, or incomplete penetration provides a location for rapid coke buildup. Excessive coke buildup at the welds causes carburization of the weld metal and adjacent tube surfaces and also results in increased metal temperature at the

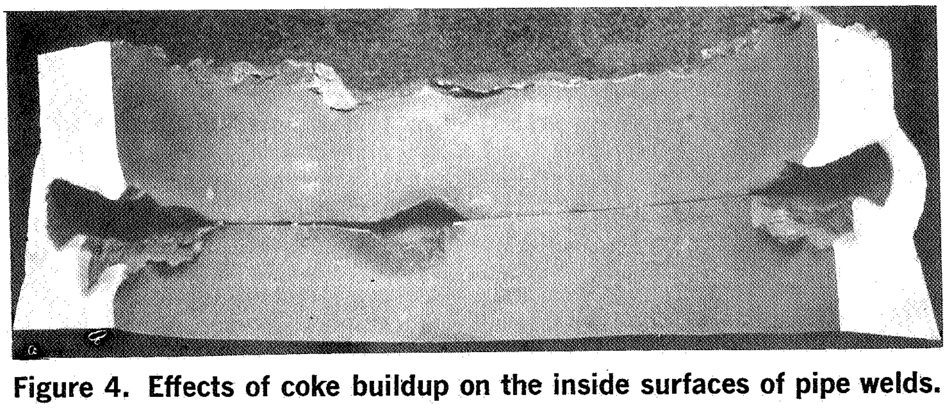

**Figure 4. Effects of coke buildup on the inside surfaces of pipe welds.**

Table 2. Effect of cold work on rupture properties of Incoloy alloy 800 (material solution-annealed prior to cold work).

| Test conditions | | Prior cold work | | | | | |
|---|---|---|---|---|---|---|---|
| | | None | | 25% tensile strain | | | |
| | | | | | | Grain size | |
| Temperature, °F | Stress, lb./sq. in. | Rupture life, hr. | Rupture elongation, % | Rupture life, hr. | Rupture elongation, % | in. | ASTM No. |
| 1,200 | 40,000 | — | — | 379.7 | 3.0 | 0.006 | 2½ |
| 1,200 | 30,000 | 221.9 | 24.0 | — | — | — | — |
| 1,400 | 18,000 | — | — | 674.2 | 4.0 | 0.006 | 2½ |
| 1,400 | 12,000 | 340.6 | 63.0 | — | — | — | — |
| 1,600 | 6,000 | — | — | 174.4 | 36.5 | 0.001-0.007 | 7½-2 |
| 1,600 | 5,000 | 864.9 | 31.0 | — | — | — | — |
| 1,800 | 3,000 | 234.9 | 36.0 | 52.1 | 46.5 | 0.0025 | 5 |

deposits. The higher temperature is caused by the coke serving as insulation against the cooling effect of the process stream. This problem is compounded during decoking of the system, because the weld must be held at temperature for a longer time before all of the coke is burned off. Both of these factors cause decreased stress-rupture life of the weld and the base metal in the areas of coke buildup.

The effects of coke buildup on a pipe weld with a poor internal surface are shown in Figure 4. The selective weld metal wastage in certain locations is apparent.

## Welding techniques

The gas tungsten arc process is widely used for the root pass of welds in furnace tubes. This process produces welds with full penetration, free from slag, and with a good root contour. The furnace tubes usually range from 3½ to 6-in. pipe size and can be readily welded by the gas tungsten arc method.

The root passes of welds in some cast stainless steel furnace tubes are made without adding filler metal. However, if wrought Incoloy alloy 800 is used on either or both sides of the weld, a filler metal should be added. The filler metal may be added by using a consumable insert or by feeding it into the joint by hand.

Consumable inserts are available in a variety of shapes. Some popular shapes are the E. B. ring, the Grinnell ring, the Kellogg ring, and the Y ring. The Y ring is widely used for hydrogen reformer applications (*3*). Regardless of the shape of insert used, the preferred composition is that of Inconel filler metal 82.

Open butt joint designs and the gas tungsten arc process with hand-fed filler metal are widely used for root passes. Joint designs are usually a standard 37½° bevel with a 1/16-in. land and a ⅛-in. root gap. The keyhole technique is used for the root pass. With this technique, the root bead is made by achieving full penetration in the weld puddle, backing off the arc, adding filler metal, then advancing the arc to a new location and repeating the procedure. Weaving is minimized because excessive melting of the sidewalls interferes with penetration and makes the interpretation of radiographic tests difficult. This technique requires relatively low welding currents, usually about 90 amp. A 3/32-in.-diameter filler wire of Inconel filler metal 82 is used.

With both the consumable insert and the hand-fed filler metal techniques, the inside of the tube should be purged with an inert gas. The gas purge is occasionally omitted in welding large furnace tubes with the hand-fed filler metal technique. The insides of unpurged welds are wrinkled by oxidation, and, at times, oxide interference in the weld puddle occurs during welding. The oxide on the weld surface is superficial in most cases, and the weld is usually sound. However, an unpurged weld bead probably develops coke deposits more rapidly than one which has been protected with an internal gas purge during welding.

In general, fill welding of furnace tubes is completed with a covered electrode, usually Inco-weld A electrode. When covered electrodes are used, all weld slag must be removed from the completed joint.

Welds in pigtail piping of hydrogen reformer systems present problems different from those in furnace tubes. The tubes are of smaller diameter, usually about 1½-in. pipe size, and, although coking is not a problem, the welds are often subjected to severe bending stresses. To withstand the stresses, the internal root contour should be as smooth as possible and slightly convex.

The gas tungsten arc method is used for the root pass of pigtail piping welds, and it is preferred that the weld be finished with this process. Consumable inserts or hand-fed filler metal may be used; inserts are usually best for small-diameter pipe. In either case, an internal gas purge should be used to obtain the best root contours. #

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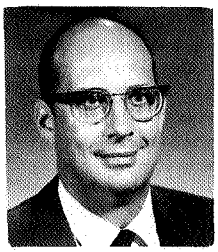

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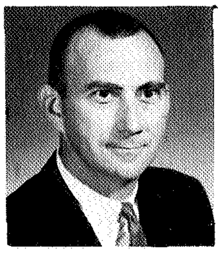

**Valentine**

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## Discussion

**Q.** On the chart where it shows the effect of cold work, at 0% cold work, the stress rupture life of Incoloy alloy 800, in a solution-annealed condition is 41.9 hours. In Bulletin T-40 on alloy 800, under these same conditions it shows a stress rupture life of 100 hours, about 2½ times greater. What is the reason for the difference?
**VALENTINE:** The data in the T-40 bulletin is for average values that are a compilation of many tests. Solution-annealed material can rupture as low as 41 hours; generally it does not. This test is apparently at the very low end of the data.
**Q.** You said that you examined six failures and determined that this material was not in the proper condition. How did you go about determining they were not?
**VALENTINE:** We examined them from grain size initially and then went back to our own laboratory procedures and resolution-annealed them according to our proscribed recommendations. We obtained grain growth which would indicate to us that temperatures not sufficient to cause solution annealing were reached. In some cases a stress rupture test was also made. The metallurgist working the tests showed most of the samples to have been annealed in the range of 1,900 °F.
**Q.** You said that you had examined some fine grain material that did have rupture strength in the same order as the solution-annealed material. What were the rupture strengths of this fine-grained material?
**VALENTINE:** I don't have the exact data with me. This phenomenon has to do with the method used to solution anneal the material: high temperature and a very rapid rate. It is a process we're not involved with personally, but we do know that it has occurred. I have seen samples that had stress rupture values of over 100 hours with a grain size of 7, but this is one company and one specific application.
**Q.** You mentioned your purging procedures in welding. We have never seen cases using stick electrodes of any problems of internal sulfur or slag attack, have you?
**AVERY:** Yes, I have.
**Q.** You said Inconel 82 weld metal was stronger than wrought Incoloy 800. I'm more interested in welding HK-40 cast tubes where the only alloys possible are Inconel 82 or a matching electrode. Can Inconel 82 get anywhere near the rupture strengths of the matching electrode?
**AVERY:** I don't have data at hand, but it is obviously less than a cast material.
**Q.** I understand there was a failure of Incoloy 800 pigtails by a sort of ex-foliation. Are you familiar with this?
**VALENTINE:** No, I have not heard of an ex-foliation problem. I have heard of some problems occurring from contamination on the O. D. of pigtails.
**Q.** One of the explanations I heard was that it was attributed to zinc from galvanized wire used on insulation, which seemed rather a far-fetched explanation.
**VALENTINE:** I am not familiar with this. The contamination problem I referred to was real, but not ex-foliation.
**Q.** Is Incoloy 800 subject to green rot?
**VALENTINE:** No.
**Q.** Would you comment on what International Nickel considers the proper stress basis for designing pigtails; either a bending stress situation or a pressure stress?
**VALENTINE:** We can only give the data and let you decide. Probably no two companies would use the identical sets of numbers.