Development of an Improved Stainless Steel to Ferritic Steel Transition Joint

Extended service life of a transition weld joint may prove possible as a result of design analysis

BY J. F. KING, M. D. SULLIVAN AND G. M. SLAUGHTER

ABSTRACT. The objective of this study was to develop an improved transition weld joint between stainless steel and ferritic steel piping to circumvent the failures and concerns with joints made by existing technology.

The primary concern of mismatch in coefficients of thermal expansion between the ferritic and austenitic steels and the high stresses that it imposes at the interface between ferritic steel and weld metal led to an extensive elastic stress analysis involving base metal combinations, filler metals, and weld joint geometries. This analysis indicated that, for pipe welds, joint stress could be reduced considerably by using a transition material with an intermediate coefficient of thermal expansion between the 2¼ Cr-1 Mo ferritic steel and the austenitic stainless steel. Alloy 800H was selected as an appropriate intermediate material for this application.

Other results of this stress analysis indicated that small angle V-groove weld joint geometries were preferable to those with large angles and that filler metals with appropriate coefficients of thermal expansion should be selected for the two weld joints required in fabricating a transition joint spool piece. ERNiCr-3 was selected for joining 2¼ Cr-1 Mo to Alloy 800H, and the inelastic analysis indicated that an iron-base austenitic stainless steel filler metal would be desirable from its thermal expansion properties for joining alloy 800H to Type 316 stainless steel. This analysis was used as a guide for the welding development program.

The welding development program initially concentrated on selecting a suitable iron-base austenitic filler metal for joining alloy 800H to Type 316 stainless steel. Various filler metals with coefficients of thermal expansion in the desired range were evaluated. The principal problems encountered were weld metal cracking and microfissuring in "cold-wire" (i.e., electrically neutral) gas tungsten arc welding. Type 16-8-2 filler metal was shown to be the least fissure-sensitive of the alloys tested. The "hot-wire" gas tungsten arc process was evaluated and found to meet the need for low weld dilution to prevent microfissuring.

Introduction

Both ferritic and austenitic stainless steels have been commonly used in commercial fossil-fired power plants for many years. The primary boilers and heat exchangers operate at low enough temperatures and under such environmental conditions that ferritic steels are the best choice for materials of construction. The higher operating temperatures of the superheater and reheater tubes, headers, and the main and hot reheat steam pipes require the use of austenitic steels. Thus, transition joints between the two types of materials are required. The experience with dissimilar metal transition joints has been generally satisfactory; however, a disturbing number of difficulties with these joints has prompted several studies into the causes of these failures over the last two or three decades.

The welding of hardenable steels and dissimilar metal welding in general began in the middle 1930's. Austenitic steel electrodes of the 18% Cr—8% Ni, 25% Cr—12% Ni, and 25% Cr—20% Ni variety were used. Many early uses of these austenitic electrodes for transition joints were with little understanding of the problems involved. This lack of understanding, together with the lack of suitable alternative filler metals, caused many failures. Beginning around 1950, the ever increasing operating temperatures in the steam power industry and the consequent aggravation of the problem led to the publishing of several technical papers covering the joining of austenitic stainless steels to ferritic steels.

Four early investigations[1-4] were conducted on transition joints of low-alloy ferritic steels (primarily of 2¼ Cr-1 Mo) to austenitic steel piping using austenitic steel filler metals. Testing of these joints under cyclic stress and temperature conditions resulted in failures in the ferritic material parallel and adjacent to the weld metal. The primary causes of failure were:

1. High stresses at the interface due to differences in coefficients of thermal expansion between weld metal and base metal.
2. Preferential stress-oxidation at the interface.
3. Accelerated creep in a narrow

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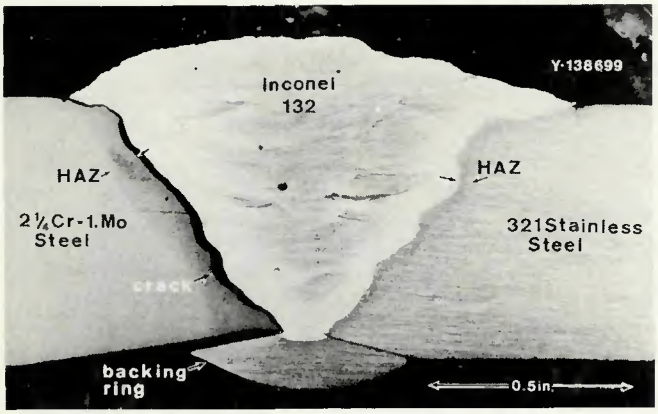


Fig. 1—Typical failure found in ferritic steel to austenitic stainless steel transition weld joints

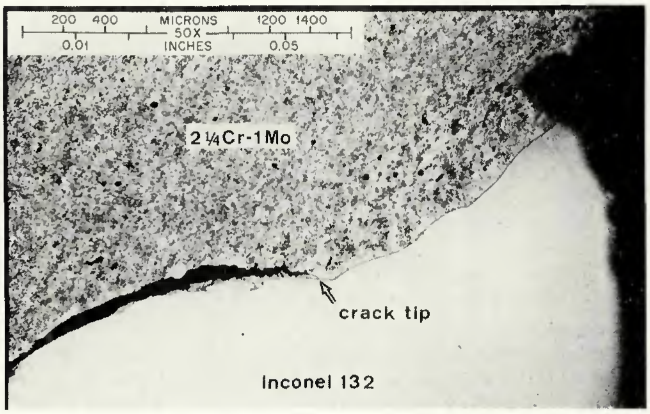


Fig. 2—A failure in transition weld joint showing the location of crack in the 2¼ Cr-1 Mo steel near the fusion line

carbon-depleted zone of the ferritic material adjacent to the interface.

Later investigations[5-9] involved testing ferritic-to-austenitic steel joints using various iron- and nickel-base austenitic filler metals. The general conclusion from this testing was that nickel-base filler metals were superior to iron-base alloys. The nickel-base weld metals greatly reduced carbon migration from the ferritic material, were highly oxidation resistant, and had coefficients of thermal expansion more nearly approached that of the ferritic material. Transition joints containing nickel-base filler metals have achieved relatively good success in cyclic high temperature applications but some failures have occurred.

A typical cross section of a failed austenitic stainless steel to ferritic steel transition joint is a transition weld joint between 2¼ Cr-1 Mo steel and Type 321 stainless steel welded with ERNiCrFe-1 (Inconel 132) filler metal—Fig. 1. This joint, 2¼ in. (63.5 mm) OD by 0.52 in. (13.2 mm) wall, was from the outlet leg of a superheater in a coal-fired utility boiler. During a service life of approximately 17 years, the joint had experienced 146 thermal cycles between ambient temperature and 1050 F (565 C). The failure occurred in the 2¼ Cr-1 Mo steel near the ERNiCrFe-1 weld metal. A higher magnification shows the crack tip as well as the path that the crack followed—Fig. 2.

The large thermal transients possible in a nuclear system such as the Liquid Metal Fast Breeder Reactor (LMFBR), together with the potential consequences of failure, made it mandatory to start a program to develop even more reliable joints and to evaluate their behavior and properties.

The first phase of this program was a design analysis done by the General Electric Co. to determine the effect of two variables—the joint materials and the joint geometry—on the thermal stresses in an austenitic-to-ferritic steel weld. This analysis led to an optimum transition joint design which minimized thermal stresses and material degradation resulting from continuous operation at 518 C (965 F) and numerous thermal transients. Only elastic stresses were considered in this analysis. A summary of the design analysis is presented below to satisfactorily introduce the welding development program which was carried out to develop satisfactory procedures for manufacturing the improved transition joint.

Selection of Materials

Unequal thermal expansion is the major cause of the high stresses in the ferritic-austenitic steel joint. The relationship between coefficients of thermal expansion (CTE) and stress is:

$$\sigma = \frac{\Delta T}{E} (\alpha_2 - \alpha_1) \qquad (1)$$

where α_1 and α_2 are coefficients of thermal expansion of the two materials, ΔT is the change in temperature of the joint, and E is the average modulus of elasticity.

For a given change in temperature ΔT, the stress is proportional to the difference in the coefficients of the thermal expansion of the two materials. Therefore, for a given dissimilar metal pair, $(\alpha_2 - \alpha_1)$ is constant, and the stress is proportional to the difference between the stress free temperature and the final temperature. For example, if the stress free temperature is assumed to be the postweld heat treatment temperature, any change from this temperature will cause stress. Assuming only elastic behavior, stresses continue to build as the materials are cooled from the stress free temperature, regardless of the cooling rate. Reheating the dissimilar pair will reduce the stresses until the zero stress temperature is reached.

It is apparent that the least severe stress situation prevails when the joint is maintained at a constant temperature close to the stress free temperature. Stresses then decrease by relaxation, which in turn lowers the creep rate and the joint reaches equilibrium. When large temperature fluctuations cannot be avoided, the effect of the difference in thermal expansion must be reduced. A practical way of doing this is to separate the dissimilar metal pair with a material or series of materials whose CTE is between those of the materials to be joined. The effect of this is to distribute the difference in the CTE over several interfaces so the mismatch at any one interface is acceptably low.

While it is apparent that thermal stresses can be reduced by the addition of materials with an intermediate CTE, metallurgical compatibility and stability during long-term service must also be considered in the choice of base metals and filler metals. This selection of suitable materials can be complicated because often the alloy composition with the proper thermal expansion is not commercially available, not approved by the ASME Code, or not easily welded.

The mean coefficients of thermal expansion for the materials considered in the joint between 2¼ Cr-1 Mo ferritic steel and Type 316 stainless steel are between the CTE of these two materials (Fig. 3) which differ from 30 to 40%. An attractive candidate for an intermediate material is alloy 800H. Other materials were ruled out in this study because they were not Code approved. The specific application of interest was a primary pressure boundary operating at 518 C (965 F) in a nuclear power plant. ASME Code Case 1592-4 limits the materials approved for this temperature range to 2¼ Cr-1 Mo steel, alloy 800H, Types 304 and 316 stainless steel.

It was also desirable to select filler metals with a CTE between those of the two base materials to be joined in each joint. A welding filler metal meeting the AWS Specification ERNiCr-3 (Inconel 82) has a CTE slightly greater than the 2¼ Cr-1 Mo steel and is a conventional filler metal in austenitic-ferritic dissimilar metal weld joints. Inconel 82 is also used for joining alloy 800H to itself. Thus, it was selected as the filler for the 2¼ Cr-1 Mo steel to alloy 800H joint. Filler metals with a CTE falling between or near those of alloy 800H and Type 316 stainless steel are the iron-base austenitics.

From this reasoning a transition joint spool piece was produced—Fig. 4. To determine if significant improvement could be obtained from this three-metal transition joint, a stress analysis compared it with a direct joint between 2¼ Cr-1 Mo steel and Type 316 stainless steel.

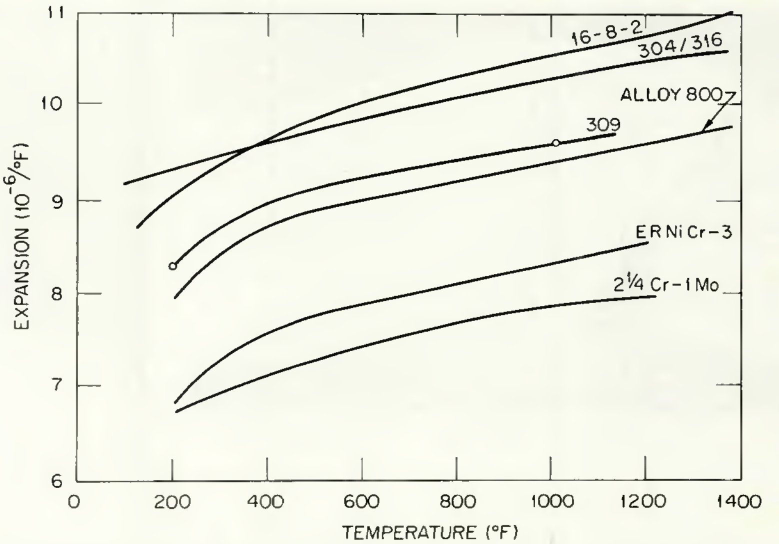


Fig. 3—Mean coefficients of thermal expansion as a function of temperature for transition joint materials

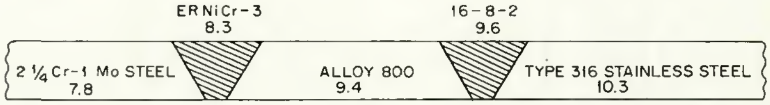


Fig. 4—Transition joint configuration being considered in this study. Mean coefficients of expansion from 21 to 538 C (70 to 1000 F) are noted below each material

Design Analysis Method

A finite element computer model was used by General Electric Co. to determine the effect of both variables—the joint materials and joint geometry—on stresses at the dissimilar metal weld. Since only the relative effect of each variable was necessary to choose the most favorable design, the most critical joint location was analyzed for each combination of material and geometry. This was a 600 mm (24 in.) OD, 13 mm (0.5 in.) wall thickness pipe operating at 512 C (965 F) with an internal pressure of 1.38 MPa (200 psig). The thermal transient used was a drop in temperature from 512 C (965 F) to 343 C (650 F) in 1000 s. The maximum rate was 1.1 C/s (2 F/s).

The contribution to the total stress was from thermal expansion mismatch, temperature gradients through the wall thickness, and the internal pressure. For this method of analysis the following assumptions were made:

1. Elastic behavior of all materials was assumed.

2. The joint was assumed to be stress-free at 732 C (1350 F).

3. The effects of dilution and decarburization on physical and mechanical properties were ignored.

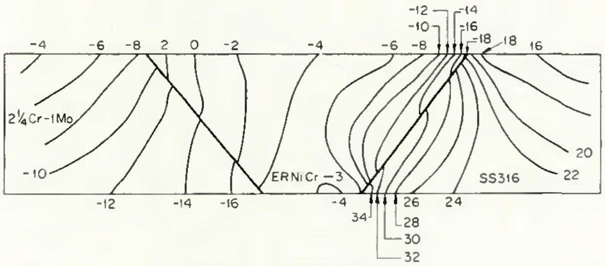
4. The fusion boundaries were assumed to be planar.

The 2¼ Cr-1 Mo steel side of the ferritic steel—ERNiCr-3—alloy 800H joint was considered to be the most likely location of failure; therefore, it was examined in more detail than the other weld in the three-metal spool piece. For comparison, a ferritic steel-to-stainless steel weld without the intermediate transition member was also analyzed.

Results of the Design Analysis

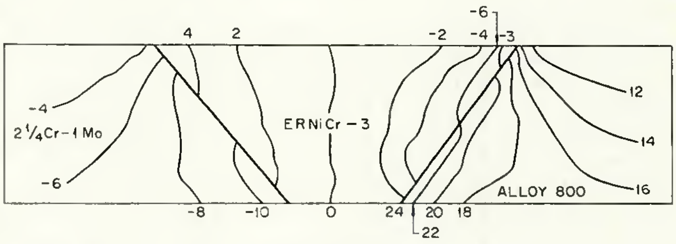
Stresses were calculated for a direct weld between 2¼ Cr-1 Mo steel and Type 316 stainless steel with a 75 deg included angle using ERNiCr-3 filler metal. A second calculation was made with alloy 800H substituted for Type 316 steel. For each of these welds hoop stress contours were prepared—Figs. 5 and 6. Symmetry is assumed around the circumference, so one section through the wall thickness represents the stress state. Hoop stresses are presented here since they represent the largest component of total stress, although axial, radial or shear stress will show the same trends.

The maximum stresses are observed to occur in approximately the same location for both of these welds. Maximum tensile stresses of 234 MPa (34 ksi) and 165 MPa (24 ksi) occur at the root tip of the Type 316 stainless steel and alloy 800H respectively. Maximum compressive stresses of 110 MPa (16 ksi) and 69 MPa (10 ksi) occur at the same location in the 2¼ Cr-1 Mo steel for the Type 316 stainless steel and Alloy 800H joint respectively. Since these are not necessarily ac-



STRESS FREE STATE 1350°F
SODIUM TEMPERATURE 650°F
STRESS IN ksi

Fig. 5—Iso-stress plot of 2¼ Cr-1 Mo-ERNiCr-3-316 stainless steel weld joint, 75 deg included angle



HOOP STRESS
STRESS FREE STATE 1350°F
SODIUM TEMPERATURE 650°F
STRESS IN ksi

Fig. 6—Iso-stress plot of 2¼ Cr-1 Mo-ERNiCr-3-Incoloy 800 weld joint, 75 deg included angle

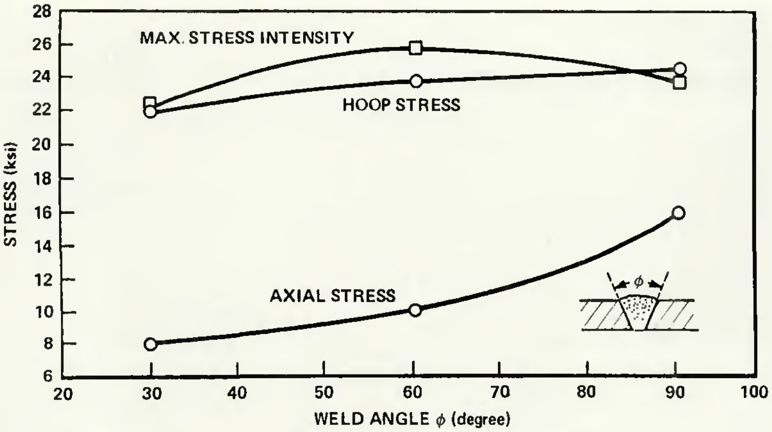


Fig. 7—Stress components as a function of weld joint angle

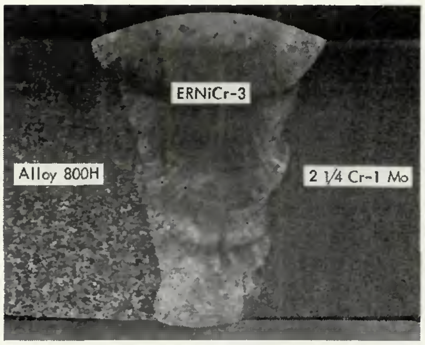


Fig. 8—Alloy 800H to 2¼ Cr-1 Mo steel transition joint weld made with automatic gas tungsten arc process using "cold wire" filler metal additions of ERNiCr-3

curate magnitudes of stress, the more important comparison is the difference in stress between the two joints. Based on this comparison, the alloy 800H joint realized a 37% decrease in peak hoop stress in the 2¼ Cr-1 Mo steel.

With the beneficial effect of the alloy 800H intermediate material clearly demonstrated, the effect of weld joint groove angle was investigated. Analyses identical to the one just described were made for the 2¼ Cr-1 Mo steel to alloy 800H joint with 90, 60, and 30 deg groove angles—Fig. 7. Peak hoop stresses in the alloy 800H decreased about 14% as the groove angle changed from 90 to 30 deg. Peak hoop stress in the 2¼ Cr-1 Mo steel was not as sensitive to groove angle, decreasing only 10% with the same change.

Maximum shear stress along the 2¼ Cr-1 Mo steel interface, believed to be a significant component in causing failure, showed a much greater dependence on joint angle. Between 75 and 30 deg groove angles, the maximum shear stress decreased from 37 MPa (5.4 ksi) to 23 MPa (3.4 ksi), a change of 37%.

The effect of joint angle on the various components of stress is seen to be less than the effect of materials. The magnitude of both hoop and shear stresses do decrease with decreasing angle, but only on the order of 13.8 to 34.5 MPa (2 to 5 ksi) while the change of material resulted in a decrease of about 69 MPa (10 ksi). When the effect of both the intermediate material and the small groove angle are added, hoop stresses in the 2¼ Cr-1 Mo steel are decreased 38%.

Based on the analysis of the effect of both the intermediate material and the weld joint angle, the reference design was selected to be 2¼ Cr-1 Mo steel welded with ERNiCr-3 to alloy 800H and the alloy 800H welded with an iron-base austenitic alloy to Type 316 or 304 stainless steel.

Welding Development

Welding development for the 2¼ Cr-1 Mo steel-alloy 800H portion of the joint concentrated on producing low dilution, defect-free deposits of ERNiCr-3 weld metal. The automatic gas tungsten arc welding process with "cold-wire" filler metal addition was used for the initial studies. Flat plate weld coupons 19 mm (0.75 in.) thick prepared with a 30 deg included angle V-groove, 4.8 mm (3/16 in.) root opening, and a backing strip were used for the welding tests—Fig. 8. It was found that defect-free welds could be produced repeatedly by this method.

The selection of a filler metal for the alloy 800H to Type 316 stainless steel presented a more significant problem. The iron-based austenitic stainless steel filler metals provided a better match of CE than nickel-base alloys for these joints but are not as easy to weld. Welding tests evaluated several potential filler metals including Types 309, 312, 347, 16-8-2 (16% Cr-8% Ni-2% Mo) and others. Initial welds were made with the automatic gas tungsten arc process using "cold wire" filler metal addition. The weldments were evaluated by radiography, dye penetrant, metallography, and bend tests.

The main problem encountered in these welds was hot cracking ranging from large cracks to microfissures. Type 347 filler metal exhibited extensive hot-cracking in the Type 316 stainless steel to alloy 800H joints (Fig. 9) and Type 16-8-2 weld metal contained the fewest microfissures—Fig. 10. The 16-8-2 is superior to the Type 347 filler metal.

Type 312 filler metal was shown to have excellent weldability with no evidence of defects or cracking in the alloy 800H to Type 316 joint. This filler metal produced weld deposits of high delta ferrite content with ferrite numbers in the range of 24 to 29. The potential problems with weld embrittlement due to transformation of the delta ferrite to sigma phase during service was sufficient reason to reject using Type 312 stainless steel filler metal. Another filler metal, Type 309, that has been occasionally recommended for transition joints, was more susceptible to hot cracking than Type 16-8-2.

These tests show that Type 16-8-2 was the best filler metal of the austenitic stainless steel class for the alloy 800H—Type 316 stainless steel joint. The fissures present were attributed to dilution of the weld metal by the alloy 800H which reduced the ferrite content of the deposit. Therefore, use of this material would require close control of the welding procedure to minimize weld dilution.

For the low-dilution requirement in these dissimilar metal welds, most of the heat input to the weld must go to melt the filler metal with only a minimum amount going into base metal melting. The "hot-wire" gas tungsten arc process was chosen to meet this requirement. In this process, the filler metal is heated by its own electrical resistance as current from an external power supply passes through it. The filler metal temperature as it reaches the puddle is just below its melting temperature. Heat input from the gas tungsten arc maintains puddle temperature and fluidity and preheats the base metals to ensure adequate side-wall fusion. A secondary advantage of the process to this application is that high deposition rates are possible.

"Hot-wire" gas tungsten arc welding procedure development was initiated on 19 mm (0.75 in.) thick plates of alloy 800H and Type 316 stainless steel. The weld joint geometry was a 30 deg included angle with a 4.8 mm (3/16 in.) root opening using a 3.2 mm (1/8 in.) thick stainless steel backing strip. This joint geometry had been used in previous welding tests using the "cold-wire" gas tungsten arc process.

The weld deposits of 16-8-2 filler metal made by the hot-wire process contained no fissures since low weld

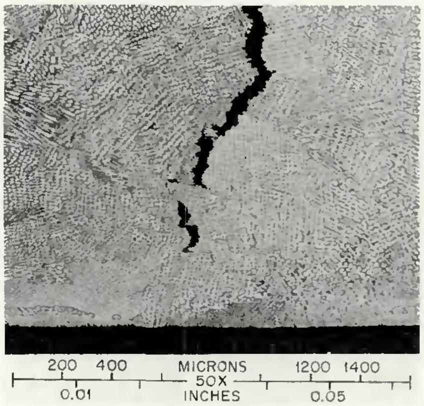


Fig. 9—Hot cracking in Type 347 weld metal used to join alloy 800H to Type 316 stainless steel

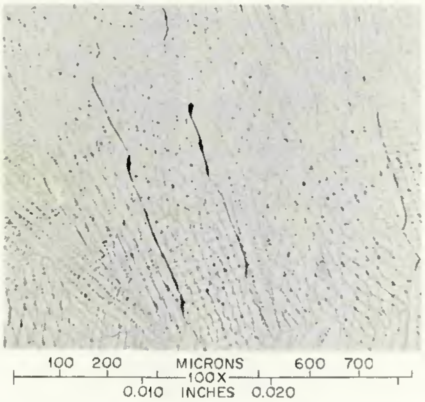


Fig. 10—Microfissures found in Type 16-8-2 weld metal used to join alloy 800H to Type 316 stainless steel

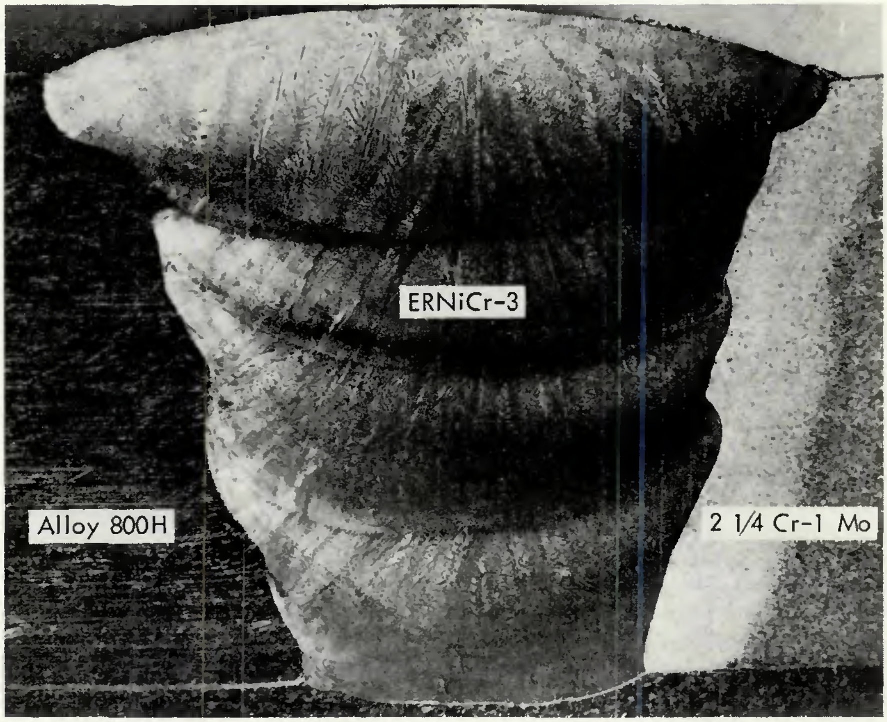


Fig. 11—Weldment of 2¼ Cr-1 Mo steel to alloy 800H made with "hot-wire" gas tungsten arc process and ERNiCr-3 filler metal

dilutions were achieved. Welds of excellent quality were achieved with the "hot-wire" process using ERNiCr-3 filler metal to join 2¼ Cr-1 Mo steel to alloy 800H. The root opening of this joint, as depicted in Fig. 11, was eventually widened to 12.7 mm (½ in.), when it was learned that this also reduced the stress level of the 2¼ Cr-1 Mo steel weld metal interface.

Conclusion

The study described in this paper was done to improve the service life of ferritic steel-to-austenitic stainless steel transition joints in piping for elevated temperature service. A 38% decrease in stress is possible at the critical ferritic steel-weld metal interface by using a material with an intermediate coefficient of expansion between the ferritic steel and austenitic stainless steel and the use of small angle weld joint geometries.

Alloy 800H was selected as an appropriate intermediate material meeting the requirements of this application. This produces a three-metal transition joint spool piece containing two welds. ERNiCr-3 filler metal was selected to join the 2¼ Cr-1 Mo ferritic steel to alloy 800H.

To match thermal coefficients of expansion between the alloy 800H and the 316 stainless steel, an iron-base austenitic filler metal is needed. Weldability studies showed that Type 16-8-2 weld metal was the least fissure sensitive between these two base materials if weld dilution was controlled to low levels. The "hot-wire" gas tungsten arc welding process was shown to be capable of making these low dilution welds.

Acknowledgments

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References

1. Lien, G. E., Eberle, F., and Wylie, R. D., "Results of Service Test Program on Transition Welds Between Austenitic and Ferritic Steels at the Phillip Sporn and Twin Branch Plants," *Transactions of the American Society of Mechanical Engineers*, 76, pp. 1075-83 (1954).
2. Emerson, R. W., Jackson, R. W., and Dauber, C. A., "Transition Joints Between Austenitic and Ferritic Steel Piping for High Temperature Steam Service," *Welding Journal*, 41(9), Sept. 1962, Research Suppl., pp. 385-s to 393-s.
3. Blaser, R. V., Eberle, F., and Tucker, J. T., "Welds Between Dissimilar Alloys and Full Size Steam Piping," *American Society for Testing and Materials, Proceedings* 50, pp. 789-807 (1950).
4. Carpenter, O. R., Jessen, N. C., Oberg, J. L., and Wylie, R. D., "Some Considerations in the Joining of Dissimilar Metals for High-Temperature, High-Pressure Service," *American Society for Testing and Materials, Proceedings* 50, pp. 809-57 (1950).
5. Tucker, J. T., and Eberle, F., "Development of a Ferritic-Austenitic Weld Joint for Steam Plant Applications," *Welding Journal*, 35(11), Nov. 1956, Research Suppl., pp. 529-s to 540-s.
6. Slaughter, G. M., and Housley, T. R., "The Welding of Ferritic Steels to Austenitic Stainless Steels," *Welding Journal*, 43(10), Oct. 1964, Research Suppl., pp. 454-s to 460-s.
7. Zemzin, V. N., "The Long Time Strengths of Welded Joints Between Austenitic Steels and Pearlite or Chromium Steels," *Welding Production* 7, pp. 1-9 (1961).
8. Gotal'skii, Yu. N., and Snisar, V. V., "Certain Special Features of the Failure of Welded Joints Between Dissimilar Steels when Subjected to Loads for Long Periods at High Temperatures," *Automatic Welding* 7, pp. 5-8 (1969).
9. King, J. F., "Behavior and Properties of Welded Transition Joints Between Austenitic Stainless Steels and Ferritic Steels—A Literature Review," ORNL-TM-5163, November 1975.