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AUSTENITIC STAINLESS STEEL-TO-FERRITIC STEEL TRANSITION JOINT WELDING FOR ELEVATED TEMPERATURE SERVICE

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Abstract

Transition weld joints between ferritic steels and austenitic stainless steels are required for fossil-fired power plants and proposed nuclear plants. The experience with these dissimilar-metal transition joints has been generally satisfactory, but an increasing number of failures of these joints is occurring prematurely in service. These concerns with transition joint service history prompted a program to develop more reliable joints for applications in proposed nuclear power plants.

1. INTRODUCTION

The welding of ferritic steels to austenitic stainless steels began in the middle 1930's. Austenitic steel electrodes of 18% Cr–8% Ni–25% Cr–12% Ni, and 25% Cr–20% Ni were used. The lack of understanding of problems involved, together with the absence of alternative filler metals, led to many failures of dissimilar metal welds during service. Beginning around 1950, the operating temperatures of the steam power industry began to increase and the problems were aggravated.

Several experimental investigations[1–4] resulted from the great interest in transition joints between low-alloy ferritic steel (primarily of the 2 1/4 Cr-1 Mo composition) and austenitic steel piping made with austenitic steel weld 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 investigators attributed the primary causes of the failure to be:

(1) High stresses at the interface due to differences in thermal coefficients of expansion between weld metal and base metal;

(2) Preferential stress-oxidation at the interface; and

(3) Accelerated creep in a narrow zone of the ferritic material adjacent to the interface, which has been weakened by migration of carbon into the austenitic weld metal.

Later investigations[5-8] involved testing of ferritic-to-austenitic steel joints made with 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 compositions. The nickel-base weld metals greatly reduced carbon migration from the ferritic material, were highly oxidation resistant, and had thermal expansion coefficients more nearly approaching that of the ferritic material. Use of the nickel-base filler metals has clearly improved the performance of transition joints in cyclic high-temperature applications, but failures have still occurred after many years of service. A more thorough discussion of the above investigations can be found in a recently published[9] literature review concerning welded transition joints.

The concerns with service history and the need for highly reliable joints in nuclear power plant piping prompted a program to develop an improved transition weld joint between austenitic stainless steel and ferritic steel. The following sections discuss some aspects of this program.

2. FAILED TRANSITION JOINT EXAMINATION

An examination[10] was made of a failed transition joint taken from a coal-fired utility boiler after a service life of approximately 17 yr. This pipe joint [63.5 mm OD × 13.2 mm wall (2 1/2 in. OD × 0.0520 in. wall)] was taken from the outlet leg of a superheater and was made of 2 1/4 Cr-1 Mo ferritic steel-to-type 321 stainless steel, welded with Inconel 132 shielded metal-arc electrodes. During the service life, the joint had experienced 146 thermal cycles between ambient temperature and 566°C (1050°F).

The failure occurred in the 2 1/4 Cr-1 Mo ferritic steel near the Inconel 132 weld metal (Fig. 1). A higher magnification view of this crack tip in Fig. 2 shows the path along which it was propagating. Several analytical techniques were utilized in the examination of this region. The findings of this investigation revealed that the crack initiated and propagated through a narrow band in the heat-affected-zone (HAZ) of the ferritic steel, very near to and paralleling the weld fusion line. The crack propagated most readily through a semi-continuous globular phase, found in some areas along the fusion line. Areas in this region with little or no globular phase present failed in an intergranular manner in the coarse-grained HAZ. The exact composition of this phase and its influence on the failure were not determined, but its presence appeared to affect the crack propagation.

In addition to the fusion line phase, other observations were made of this region. The dislocation density in the 2 1/4 Cr-1 Mo steel increased markedly near the fusion line. This condition is probably related to the high stresses created by the cyclic temperature service. It was also found that a sharp increase in hardness occurred in a narrow band in the weld metal adjacent to the fusion line. The formation of carbide precipitates in this region caused the hardness increase and indicates carbon diffusion from the ferritic steel to the weld metal.

An exact failure mechanism could not be determined from this examination, but it was reaffirmed that transition joint design is very important. The basic concerns that have been recognized for many years are still applicable, including:

(1) Select filler metals that minimize migration of carbon from the ferritic steel;
(2) Minimize the differences in coefficients of thermal expansion between the metals in the joint; and
(3) Minimize stresses at the weld interfaces.

3. TRANSITION JOINT DESIGN

A study[11] was conducted to establish the design of piping transition joints for a liquid metal fast breeder reactor plant. The basic materials to be joined are 2 1/4 Cr-1 Mo ferritic steel and type 316 austenitic stainless steel. The mismatch in thermal expansion properties of these two materials is the major cause of high stresses at the ferritic steel-austenitic steel weld joint during cyclic temperature service. The least severe stress situation occurs when the joint is maintained at a constant temperature, since the stress level will decrease by relaxation, which in turn lowers the creep rate and the joint reaches equilibrium. When large temperature fluctuations cannot be avoided, as in this case, 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 coefficient of thermal expansion (CTE) are between those of the two to be joined. The effect of this is to distribute the difference in CTE over several interfaces so that the mismatch at any one interface is acceptably low.

The coefficients of thermal expansion were examined for a number of materials considered for use in the joint between 2 1/4 Cr-1 Mo and type 316 stainless steel (Fig. 3). An attractive candidate for an intermediate material is alloy 800H. Other materials were ruled out because they were not approved for use in this application by ASME Code Case 1592 which limits materials to 2 1/4 Cr-1 Mo steel, alloy 800H, and types 304 or 316 stainless steel. It was also desirable to select welding filler metals which have a CTE between the base materials to be joined in each joint.

A welding filler metal meeting AWS specification ERNiCr-3 (commonly known as Inconel 82) has a CTE slightly greater than the 2 1/4 Cr-1 Mo steel. This filler metal, conventionally used in austenitic/ferritic dissimilar weld joints, was selected for the 2 1/4 Cr-1 Mo steel to alloy 800H joint. Filler metals with CTE falling between or near the alloy 800H and type 316 stainless steel are the iron base austenitics. It was concluded after evaluation of several filler metals of this class that type 16-8-2 (16% Cr—8% Ni—2% Mo) was the best choice for this application. These considerations produced a transition joint spool piece design with a gradual change in expansion properties (Fig. 4).

4. DESIGN ANALYSIS

To determine if significant improvement could be obtained from this three-metal transition joint, a detailed stress analysis was performed to compare it with a conventional direct joint between 2 1/4 Cr-1 Mo steel and type 316 stainless steel. A finite element computer model was used to determine the effect of both the joint materials and joint geometry on stresses at the dissimilar metal weld. An elastic analysis was performed on a 600-mm (24-in.) OD, 13-mm-wall (0.5-in.-wall) thickness pipe operating at 519°C (965°F) with an internal pressure of 1.104 MPa. The thermal transient used was a drop in temperature from 519°C (965°F) to 343°C (650°F) in 1000 sec. The contribution to the total stress was from three sources: (1) thermal expansion mismatch, (2) temperature gradients through the wall thickness, and (3) internal pressure.

Stresses were calculated for a direct weld between 2 1/4 Cr-1 Mo and type 316 with a 75° included angle using ERNiCr-3 filler metal. A second calculation was made with alloy 800H substituted for type 316. The maximum stresses were observed to occur at the same location for both of these welds (Figs. 5 and 6). Maximum tensile stresses occur at the inside diameter in the type 316 or alloy 800H adjacent to the weld. The maximum compressive stresses occur at the same location in the 2 1/4 Cr-1 Mo steel. Comparison of these two joint types revealed the use of alloy 800H in the transition joint provided a 37% decrease in peak hoop stress in the 2 1/4 Cr-1 Mo steel. Hoop stresses represent the largest component of total stress.

The effect of weld joint groove angle was investigated after the beneficial effect of alloy 800H was demonstrated. Analyses identical to the one just described were made for the 2 1/4 Cr-1 Mo steel/alloy 800H joint with 90, 60, and 30° included groove angles. It was found that both hoop and shear stresses decrease with decreasing angle, but by a smaller amount than resulted from the use of alloy 800H. When the effect of both the alloy 800H and the small groove angle are added, hoop stresses in the 2 1/4 Cr-1 Mo steel are decreased by 38%.

5. DISCUSSION

Austenitic stainless steel to ferritic steel transition joints for elevated-temperature service continue to be an area of concern. Failures of these joints in fossil-fired electrical generating plants can result in shutdowns at times when all generating capacity available is needed. Similar problems may be faced by future breeder reactor plants. The continuing effort to improve transition joint service life may ultimately produce an economical and reliable solution to the problem. An understanding of the contributing factors to early failure plus careful design of future joints offers areas of improvement. The work described in this paper has guided the welding development programs[12] for producing transition joint spool pieces intended for future nuclear service. Base materials and weld filler metals were selected to reduce the mismatch in coefficients of thermal expansion. Also, a filler metal was selected to minimize the carbon migration problem from the ferritic steel. Various testing programs are being conducted to characterize the benefit of these joints using intermediate materials and hopefully gain information for predicting service life expectancy.

6. CONCLUSIONS

Studies have been conducted to gain insight into the failure mechanisms and improve the service life of ferritic to austenitic steel transition joints. Failures of these joints are attributed to metallurgical changes in the HAZ of the welds and creep-fatigue damage resulting from the mis-match of thermal expansion properties of the materials and the cyclic temperature service. It has been found by finite element analysis techniques that a 38% decrease in stress is possible at the critical ferritic steel-weld metal interface by: (1) using a material with an intermediate coefficient of thermal expansion between the ferritic steel and austenitic stainless steel, and (2) the use of small angle weld joint geometries.

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8. BIOGRAPHIES

J. F. King is a development engineer in the Welding and Brazing Group of the Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee. He received the BWE degree from Ohio State University in 1968. At that time, he joined the Oak Ridge Y-12 Plant in the Development Division Welding Group. From 1974 to present, he has worked at the Oak Ridge National Laboratory.

G. M. Goodwin received the Ph.D degree from Rensselaer Polytechnic Institute in 1968. He is currently Group Leader of the Welding and Brazing Group in the Metals and Ceramics Division, Oak Ridge National Laboratory. His areas of interest include filler metal and procedure development for joining stainless steels, nickel-base alloys, and development of equipment and techniques for automated welding of pipe in a variety of alloys.

G. M. Slaughter, Manager, Engineering Materials Section of the Metals and Ceramics Division, Oak Ridge National Laboratory has studied the welding behavior of a wide range of iron- and nickel-base materials as well as refractory metals, and has developed procedures for joining of these materials into reactor components.

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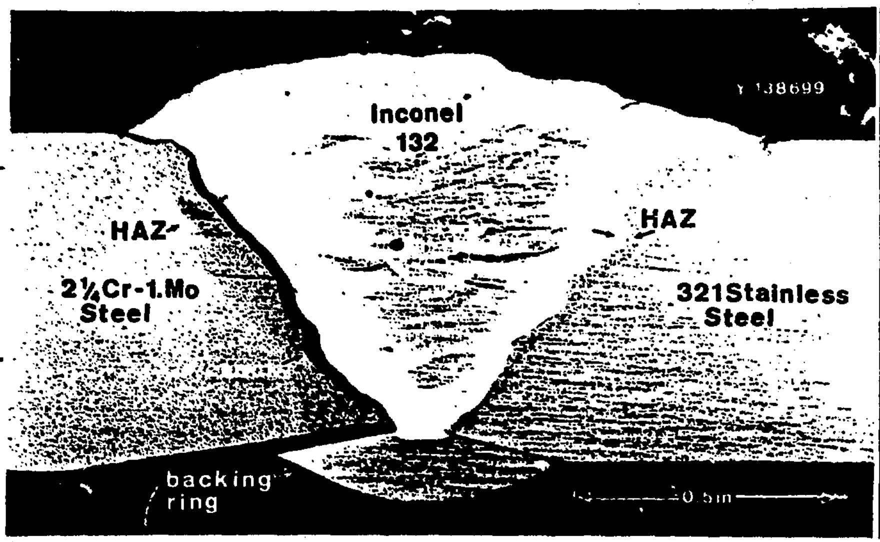

FIG. 1. TYPICAL FAILURE FOUND IN FERRITIC STEEL-TO-AUSTENITIC STAINLESS STEEL TRANSITION WELD JOINTS.

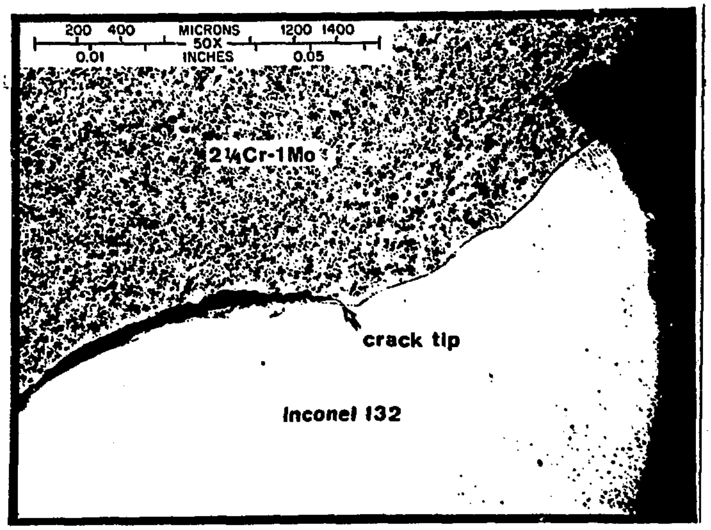

FIG. 2. A FAILURE IN TRANSITION WELD JOINT SHOWING THE CRACK TIP IN THE 2 1/4 Cr-1 Mo STEEL NEAR THE FUSION LINE.

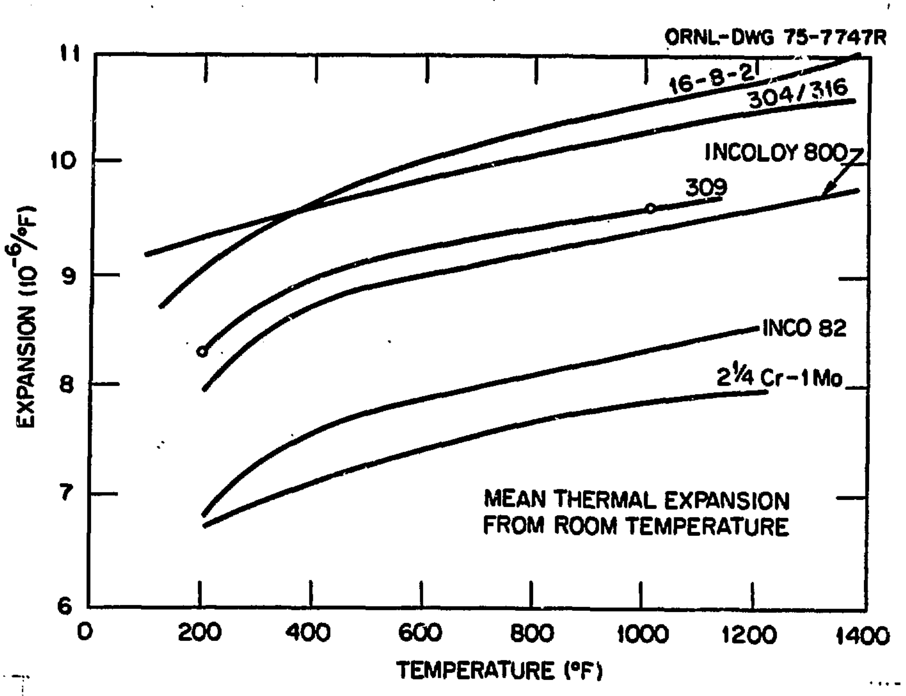

FIG. 3. MEAN COEFFICIENTS OF THERMAL EXPANSION AS A FUNCTION OF TEMPERATURE FOR TRANSITION JOINT MATERIALS.

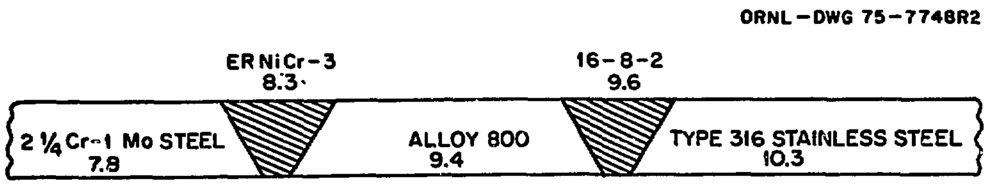

FIG. 4. TRANSITION JOINT CONFIGURATION DEVELOPED IN THIS STUDY. MEAN COEFFICIENTS OF THERMAL EXPANSION FROM 21 to 538°C (70 to 1000°F) ARE NOTED BELOW EACH MATERIAL.

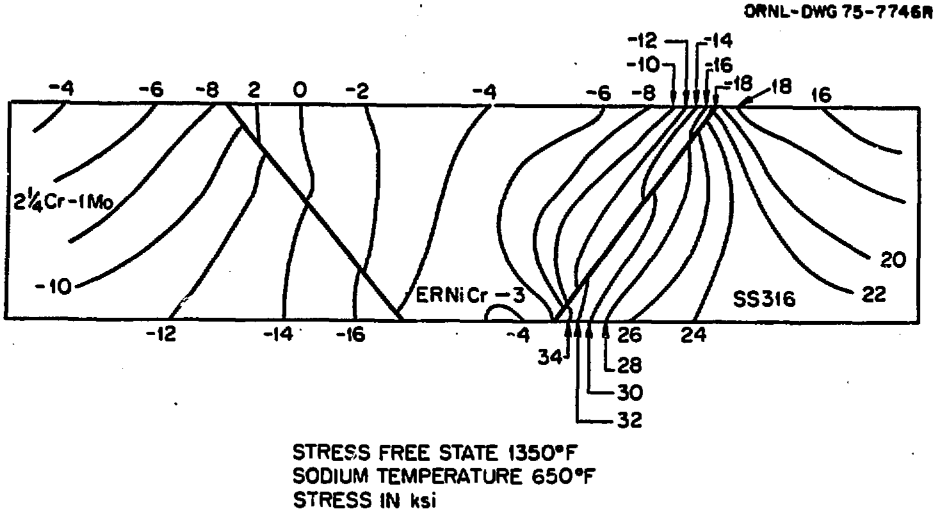

FIG. 5. ISO-STRESS PLOT OF 2 1/4 Cr-1 Mo ERNiCr-3/316 STAINLESS STEEL WELD JOINT, 75° INCLUDED ANGLE.

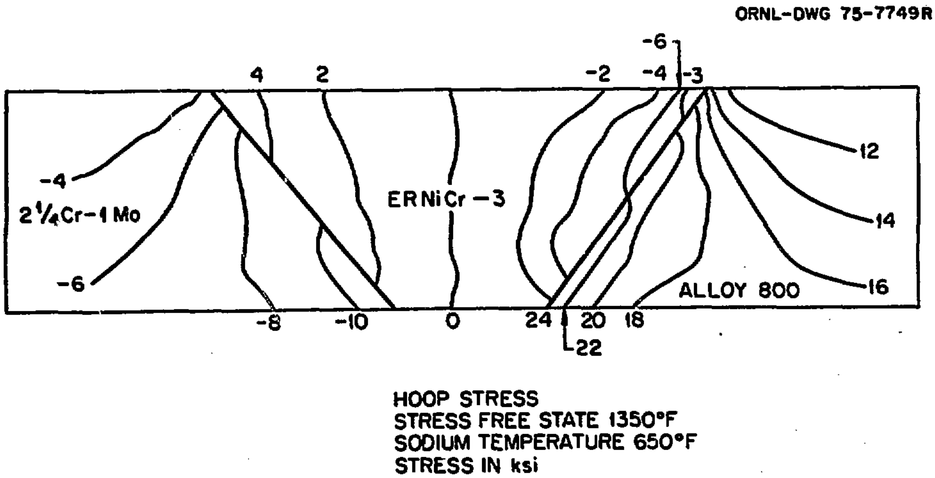

FIG. 6. ISO-STRESS PLOT OF 2 1/4 Cr-1 Mo/ERNiCr-3/ALLOY 800H WELD JOINT, 75° INCLUDED ANGLE.