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A New Fe-Ni-Co-Cr Filler Metal for Joining Alloy 800H

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ABSTRACT

The use of HAYNES® alloy No. 556 as a filler metal for joining alloy 800H or 800HT was assessed. Alloy 800H weld joints using alloy 556 filler metal were characterized in terms of structural integrity, tensile and creep-rupture properties and thermal stability. The studies have concluded that alloy 556 filler metal produces good, sound quality weld joints of alloy 800HT. The major characteristics of alloy 800HT weldments using alloy 556 filler metal are presented in comparison with those using a high-nickel filler metal such as INCONEL® alloy 82.

INTRODUCTION

Alloy 800H is a stable austenitic Fe-Ni-Cr alloy widely used for high temperature applications in industry. Nevertheless, alloy 800H is frequently welded with high-nickel filler metals such as alloy 82 (ERNiCr-3) in order to avoid hot cracking problems. For many applications in metallurgical and mineral processing, refinery, chemical and petrochemical processing, fossil power generation, coal gasification and fluidized-bed combustion, sulfidation has been considered to be an important mode of high temperature corrosion. (1-5) It is well known that high-nickel alloys are very susceptible to sulfidation attack. They tend to form nickel sulfides which melt at approximately 1200°F (648°C). Thus, the industry is in need of a low-nickel, high-strength, austenitic filler metal that is compatible with alloy 800H or 800HT.

Several studies(6,7) have been conducted on alloy 800H weldments using different filler metals. Both Natesan(6), and Verma and Schaefer(7) performed the exposure tests on weldment samples in gaseous environments typical of coal gasification environments. Natesan evaluated filler metals of alloy 82, Marathon 21/33, Marathon 25/35, Marathon 25/35R, Marathon 30/50 and Marathon 50/50Nb; while Verma and Schaefer evaluated FM617, FM72, FM88, and WE188, among other filler metals. Both studies have indicated that high-nickel weld metals can accelerate the oxidation/sulfidation process in the weldment. The above studies, however, failed to investigate (a) the weldability of alloy 800H using different filler metals, (b) metallurgical integrity of the weld joints, and (c) mechanical properties of the weldments.

HAYNES alloy No. 556 is a stable austenitic Fe-Ni-Co-Cr alloy. The alloy is a modified version of MULTIMET® alloy (or alloy N-155). It was developed and introduced into the market in the late 1970's. With the control of several minor elements such as Ta, Zr and La, the alloy possesses good oxidation, weldability, formability, and creep strengths.(8) Alloy 556 has at least 100°F temperature advantage in oxidation resistance over MULTIMET alloy. Furthermore, the alloy has been found to exhibit good sulfidation resistance,(9) good chlorination resistance(10) and good performance in waste incineration environments.(10,11) The alloy is now being used in mineral/metallurgical processing, chemical/petrochemical/refining operations, pulp and paper recovery boilers, fluidized-bed combustors and waste incinerators. Based on the characteristics and attributes of alloy 556, it appears that the alloy would be suitable for use as a filler metal for joining alloy 800H or 800HT. An investigation was then undertaken to determine the integrity of the alloy 800HT weld joints using alloy 556 as a filler metal.

EXPERIMENTAL PROCEDURE

Welds were made by joining 1/2-inch thick alloy 800HT plates using alloy 556 filler metal. Alloys 82 and 625 were also used as filler metals for comparison. The nominal compositions of base metal alloy 800HT and filler metal alloys 556, 82 and 625 are shown in Table 1. A 60°V-groove and a root gap of 1/8-inch were used. Welding was performed using gas-tungsten-arc welding (GTAW) process with 1/8-inch diameter weld wire. Argon was used for shielding.

The test weldment specimens were obtained from welded plates with reduced section consisting of weld metal in the middle and base metal on both sides. The all-weld metal (AWM) specimens were obtained by electro-discharge machining within the weld metal with the specimen axis parallel to the welding direction. These AWM specimens include only the metal in the fusion zone.

Weldments of alloy 800HT using different filler metals were evaluated in terms of weld quality, mechanical properties and thermal stability. Evaluation of the weld quality involved guided-bend testing,(12) visual and microscopic examination. The resistance to microfissuring was determined using the fissure bend test (13) and metallographic examination of the weld metal.

The sample for the fissure bend test was a 1/4 x 1 x 8 inch weld pad deposited on a 1/2 x 2 x 9 inch base plate. The pad contained two layers of weld overlays. Alloy 800H was used as a base plate material. The weld pad was surface ground to a surface finish of about 90 rms. The test was conducted using a 3 point bending with a 3/4-inch die radius. The test procedures are described elsewhere.(13) The sample is then examined for fissures.

Tensile and creep-rupture tests were performed on transverse weldment specimens and AWM specimens. Thermal stability was determined by measuring the residual room temperature tensile ductilities after aging at 1200, 1400, and 1600°F (649, 760 and 871°C) for 1000 hours. Test specimens were machined from weldment blanks after aging.

RESULTS AND DISCUSSION

Sulfidation Resistance

It is important that the filler metal selected will exhibit the sulfidation resistance at least as good as the base metal. The behavior of alloy 556 in sulfidizing environments has been reported in earlier papers.(9,11) Both laboratory and field tests have indicated that alloy 556 is significantly better than alloy 800H and high-nickel alloys such as alloy 600. Figure 1 illustrates the sample cross sections of alloys 556, 800H and 600 tested at 1600°F (871°C) for 215 hours in Ar-5%H_2-5%CO-1%CO_2-0.15%H_2S (by vol. pct). The equilibrium partial pressures of oxygen and sulfur for the gas mixture at the test temperature (i.e., 1600°F) were calculated to be 3×10^{-19} atm and 0.9×10^{-6} atm, respectively. Alloy 600 was sulfidized throughout the sample thickness. Nickel-rich sulfides (light grayish phases) as well as Cr-rich sulfides (dark grayish phases) were observed to form in alloy 600 (Fig. 1c). The alloy 800H sample, although not completely sulfidized, suffered severe sulfidation attack. Alloy 556 suffered the least attack. Sulfidation testing in the same gas mixture at 1400°F (760°C) for 215 hours essentially showed the similar results. This is illustrated in Fig. 2 In the figure, alloy 556 was compared with alloy 800H and alloy 625 (a high-nickel alloy).

All the above samples tested were obtained from wrought materials. It is not expected to see alloy 556 weld metal would behave differently. The alloy 556 vessels that have been in service in the field have not indicated any differences in sulfidation resistance between the weld metal and the base metal. Nevertheless, laboratory testing of 800HT/556 weld/800HT weldments is currently underway.

Weldment Characterization

A typical weldment consisting of alloy 800HT base plates joined by alloy 556 filler metal is shown in Fig. 3. A sound joint was produced. Visual examination of the weld joints showed no cracking.

The guided-bend test with a 2T (2 x thickness) bend radius was used to evaluate the ductility and soundness of the weld joint. Face and root bends reveal defects near the respective weld surfaces while side bends tend to reveal internal defects, such as underbead microfissuring. No cracks or other discontinuities were detected in the 800HT/556/800HT weld joint as shown in Fig. 4, indicative of good weld joints. The face and root bends are also a good measure for the weldments ductility.

To evaluate the resistance to weld metal microfissuring of alloy 556, the fissure bend test was performed. This test provides a more rigorous evaluation than the guided-bend test. The detailed discussion of the fissure bend test can be found in a paper by Lundin et al.(13) The specimens after testing are shown in Fig. 5. Alloy 556 was found to behave very similarly to alloy 82. One tiny fissure was detected after bending alloy 556 weld metal. In an alloy with poor resistance to weld metal fissuring, the number of cracks produced by this test typically run in excess of fifty. Alloy 82 was designed specifically as a weld filler metal with low hot crack susceptibility.

Macroscopic examination of the weldment was conducted to determine the weld dilution and the metallurgical soundness of the weld. The examination failed to reveal any defects. A typical cross section of the weld is shown in Fig. 6. The dilution of alloy 800HT in the alloy 556 weld metal was estimated to be less than 10 percent. If a nickel-base filler metal is used, it is desirable to keep the iron dilution from alloy 800HT to a minimum in order to avoid weld metal hot cracking. However, since alloy 556 is an Fe-Ni-Co-Cr alloy, minor iron enrichment from weld dilution is not considered to be a concern.

Microstructural evaluation revealed the nature of the fusion boundary and weld solidification structure. Figure 7 shows the interface between the alloy 800HT base metal and alloy 556 weld metal. The austenitic grain structure of alloy 800HT at the weld pool edge acts as an ideal site for the alloy 556 grains to grow. This "epitaxial" weld metal solidification results in a continuous grain across the fusion boundary. Examination of the weld metal microstructure shown in Figure 8 indicates a cellular dendritic solidification mode. Figure 8a shows the interface between two weld passes. The reheating of the earlier pass by the subsequent pass reduced the second phase precipitation seen along cell boundaries. It is common in multipass welding for migration of crystallographic grain boundaries from the original solidification boundaries to occur during reheating. In the case of alloy 556, limited grain boundary migration has occurred. These grain boundaries are expected to be more resistant to intergranular cracking (greater crack path tortuosity) than a straightened boundary.

Mechanical Properties of Weldment

(a) Tensile Properties:

Tensile tests were performed at room and elevated temperatures. Fracture generally occurred in the alloy 800HT base metal, away from the heat-affected zone, as illustrated in Fig. 9. The tensile data are tabulated in Table 2. The weldment exhibited good tensile ductility. The tensile ductility of the alloy 556 weld metal was also evaluated. It was compared to those of alloys 82 and 625. The results are given in Table 3. Alloy 556 weld metal was shown to exhibit room temperature tensile ductility similar to alloy 625 weld metal.

(b) Thermal Stability:

Prolonged exposure to intermediate temperatures (i.e., 1000-1600°F) during service can result in ductility loss in many high temperature alloys. This ductility loss is generally associated with the precipitation of carbides and/or intermetallic compounds. The thermal stability of the weld joint and weld metal were evaluated by determining the residual tensile ductility after aging both the transverse weldment samples and all weld metal samples. The effect of thermal aging on the room temperature tensile properties of the 800HT/556/800HT weldment is summarized in Table 4. All specimens broke in the alloy 800HT base metal. Most plastic deformation occurred in the alloy 800HT base metal with the exception of the specimens aged at 1200°F (649°C), where alloy 800HT has undergone considerable strengthening.

The thermal aging data for all-weld metal (AWM) samples for weld metal 556, 82 and 625 are shown in Tables 5, 6 and 7. Alloy 556 weld metal was shown to exhibit reasonably good residual room temperature tensile ductility (better than that of alloy 625 weld metal) after aging for 1000 hours at 1200 and 1400°F (649 and 760°C).

(c) Creep Rupture Properties:

Creep-rupture strength is an important consideration for alloys to be used at elevated temperatures. Tests were performed on both transverse weldment and AWM specimens to evaluate the creep-rupture behavior at 1400 and 1600°F (760 and 871°C). The results are summarized in Figures 10 and 11. The AWM specimens were slightly stronger than alloy 556 wrought product. The transverse 800HT/556/800HT weldment specimens were stronger than wrought alloy 800HT. This strengthening is presumably due to the contribution of alloy 556, which is inherently stronger than alloy 800HT.

The AWM data for alloy 556 is also compared to published data for alloys 82 and 625 weld metals.(14,15) Figure 12 suggests alloys 556, 625 and 82 all possess adequate 1400°F rupture strength for use with alloy 800HT. Figure 13 shows that, at 1600°F, the rupture strength of alloy 82 weld metal is significantly lower than that of alloy 800HT. Thus, alloy 82 filler metal is not suitable for joining alloy 800HT for applications at 1600°F (871°C). Bauford and Hosier(16) advised that Alloy 82 is not recommended for welding alloy 800HT for applications above 1450°F. At both test temperatures, alloy 556 weld metal retains superior rupture strength as compared to wrought alloy 800HT.

SUMMARY AND CONCLUSIONS

1. Alloy 556 filler metal produces a sound quality weld joint for alloy 800HT.

2. Alloy 556 shows good resistance to weld metal microfissuring during multi-pass weld operations.

3. Alloy 556 weld metal has adequate tensile and creep-rupture strengths as that compared to alloy 800HT base metal.

4. Alloy 556 weld metal undergoes a moderate reduction in ductility following thermal exposure at 1400°F. This ductility reduction is not as severe as observed in alloy 625 weld metal.

5. Alloy 556 possesses a sulfidation resistance better than alloy 800HT.

6. Based on the results of the current investigation, alloy 556 is a suitable filler metal for joining alloy 800H or 800HT for high temperature applications, particularly in sulfidizing environments where the traditional high-nickel filler metals are not suitable.

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TABLE 1

Nominal Compositions (wt.%) of alloy 800HT Base Metal and alloys 556, 82 and 625 Filler Metals

	Alloy 800HT	Alloy 556	Alloy 82	Alloy 625
Ni	32.5	20	Bal	Bal
Co	-	18	-	-
Cr	21	22	20	21.5
Mo	-	3.0	-	9.0
W	-	2.5	-	-
Fe	Bal	Bal	1.0	2.5
Si	0.5	0.35	0.2	0.2
Mn	0.8	1.0	3.0	0.2
C	0.08	0.10	0.02	0.05
Al	0.5	0.20	-	0.2
Ti	0.5	-	0.6	0.2
Cu	0.4	-	0.04	-
N	-	0.20	-	-
Others		Zr-0.02 La-0.02 Cb+Ta 0.80	Cb-2.5	Cb+Ta-3.6

TABLE 2

Tensile Test Results(1) of Transverse Weldment Specimens of Alloy 800HT using Alloy 556 Filler Metal (800HT/556/800HT)

Test Temperature °F (°C)	0.2% YS ksi (MPa)	UTS ksi (MPA)	% El(2)	% RA
RT	47.4 (327)	85.9 (593)	36.2	58.4
1200 (649°C)	25.7 (177)	66.4 (458)	40.2	43.7
1400 (760°C)	25.8 (178)	44.7 (308)	30.6	48.6
1600 (871°C)	20.0 (138)	24.4 (168)	25.6	69.8

(1) average of two tests
(2) % El in 1.25 inches; fracture occurred in the alloy 800HT base metal

TABLE 3

Room Temperature Tensile Properties(1) of All-Weld Metal (AWM) Specimens

Alloy	0.2% YS ksi (MPa)	UTS ksi (MPA)	% El(2)	% RA
556	70.1 (484)	109.7 (757)	35.8	39.3
625	71.0 (490)	116.2 (802)	40.4	41.8
82	54.0 (373)	101.6 (701)	44.1	47.1

(1) average of two tests
(2) % El in 1.25 inch

TABLE 4

The Effect of Thermal Aging on Room Temperature Tensile Properties(1) of Transverse Weldment Specimens (800HT/556/800HT)(2)

Condition	0.2% YS ksi (MPa)	UTS ksi (MPA)	% El(2)	% RA
As-welded	47.4 (327)	85.9 (593)	36.2	58.4
Aged 1200°F (699°C)/1000hrs	71.6 (494)	111.6 (770)	24.5	36.1
Aged 1400°F (760°C)/1000hrs	52.7 (364)	91.0 (628)	28.4	49.1
Aged 1600°F (871°C)/1000hrs	45.3 (312)	86.9 (600)	32.6	54.2

(1) average of two tests
(2) % El in 1.25 inches; fracture occurred in the alloy 800HT base metal

TABLE 5

Effect of Thermal Aging on Room-Temperature Yield Strength* of All Weld Metal (AWM)

	0.2% Offset Yield Strength, ksi (MPa)		
Condition	Alloy 556 AWM	Alloy 626 AWM	Alloy 82 AWM
As-welded	70.1 (484)	71.0 (490)	54.0 (373)
Aged 1200°F (649°C)/1000hrs	71.6 (494)	94.2 (650)	66.7 (460)
Aged 1400°F (760°C)/1000hrs	71.5 (493)	69.1 (480)	51.4 (355)
Aged 1600°F (871°C)/1000hrs	59.5 (411)	58.2 (402)	47.1 (325)

* average of two tests

TABLE 6

Effect of Thermal Aging on Room-Temperature Tensile Strength* of All Weld Metal (AWM)

	Ultimate Tensile Strength, ksi (MPa)		
Condition	Alloy 556 AWM	Alloy 625 AWM	Alloy 82 AWM
As-welded	109.7 (757)	116.0 (800)	101.0 (697)
Aged 1200°F (649°C)/1000hrs	117.2 (809)	130.9 (903)	113.1 (780)
Aged 1400°F (760°C)/1000hrs	109.2 (753)	112.9 (779)	100.4 (693)
Aged 1600°F (871°C)/1000hrs	108.8 (751)	115.9 (800)	101.0 (697)

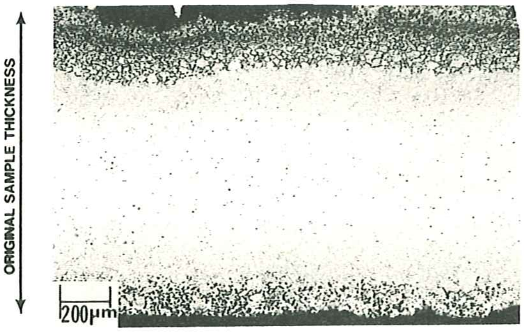
* average of two tests

TABLE 7

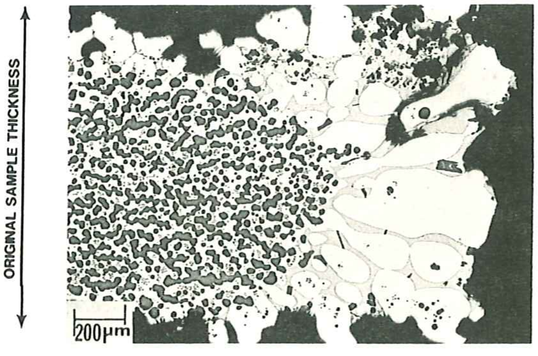
Effect of Thermal Aging on Room Temperature Tensile Elongation* of All Weld Metal (AWM)

	Tensile Elongation, Percent		
Condition	Alloy 556 AWM	Alloy 625 AWM	Alloy 82 AWM
As-welded	35.8	40.4	44.1
Aged 1200°F (649°C)/1000hrs	24.4	20.0	34.5
Aged 1400°F (760°C)/1000hrs	18.0	11.6	43.9
Aged 1600°F (879°C)/1000hrs	22.7	27.1	46.8

*elongation in 1.25 inches, average of two tests



Alloy 556



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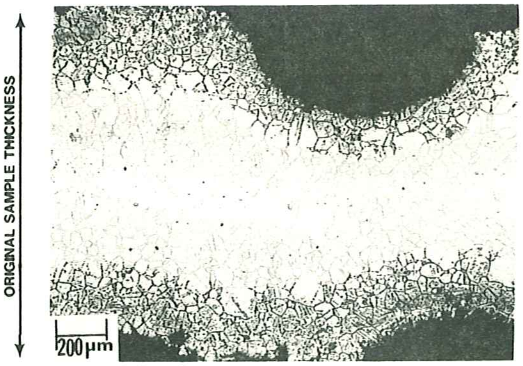

Alloy 800H

FIGURE 1: Cross-section of samples tested in Ar-5%H_2-5%CO-1%CO_2-0.15%H_2S at 1600°F (871°C) for 215 hours. Samples were cathodically descaled following sulfidation testing. The alloy 600 sample was completely sulfidized. As-polished.

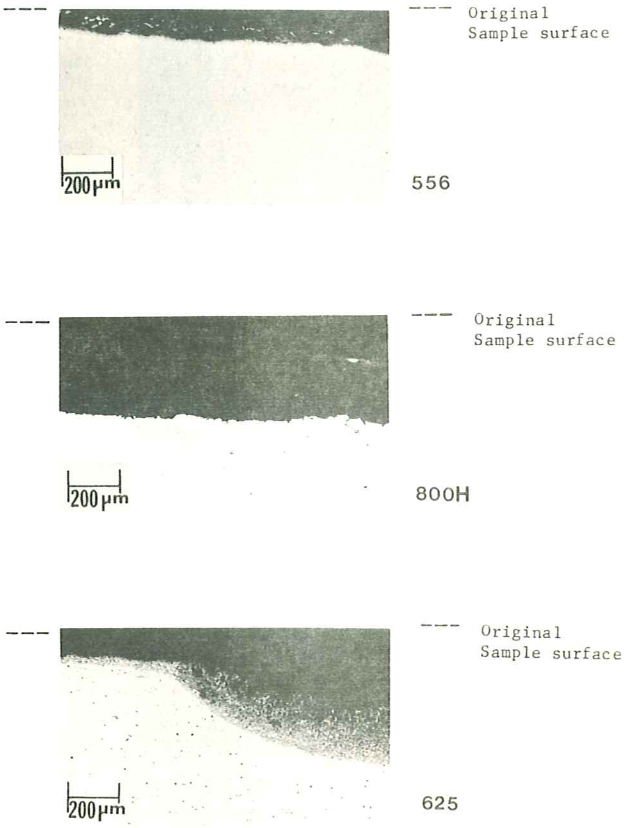

FIGURE 2: Cross-section of samples tested in Ar-5%H_2-5%CO-1%CO_2-0.15%H_2S at 1400°F (760°C) for 215 hours. Samples were cathodically descaled following sulfidation testing. As-polished.

FIGURE 3: Weldment consisting of 1/2-inch thick alloy 800HT plates gas-tungsten-arc welded using alloy 556 filler Metal (800HT/556/800HT).

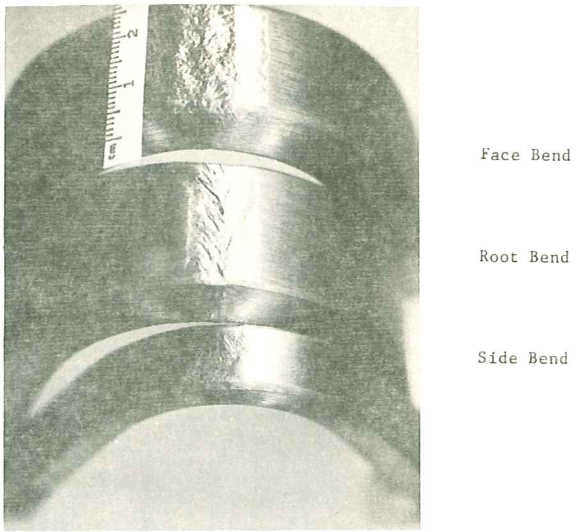

FIGURE 4: Typical guided bend test specimens (2T bend radius) of 800HT/556/800HT weldment.

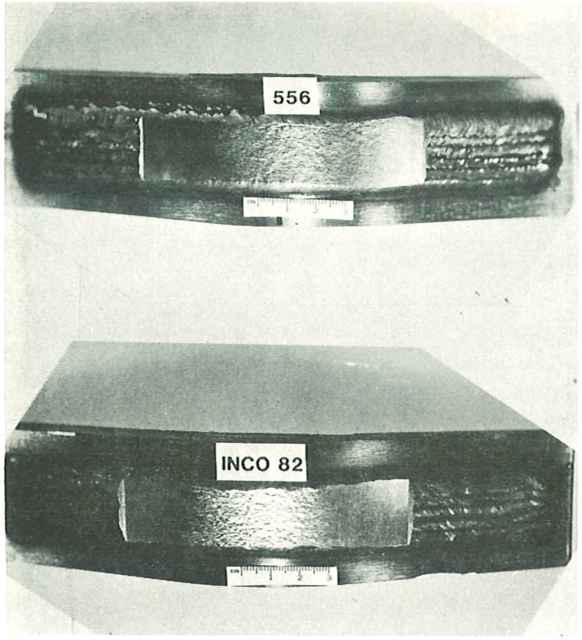

FIGURE 5: Fissure bend test specimens of alloys 556 and 82 weld metals.

FIGURE 6: Cross-section of the 800HT/556/800HT weldment.

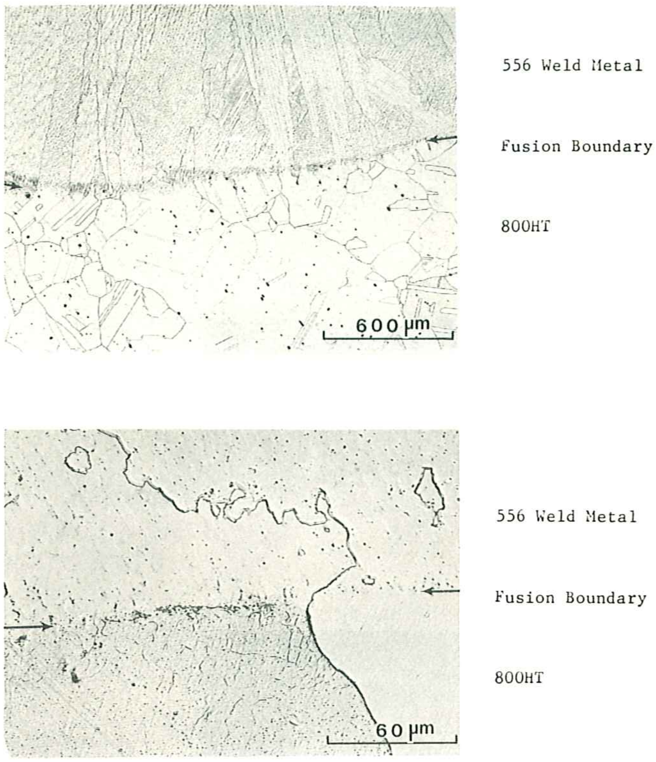

FIGURE 7: Fusion boundary between alloy 800HT base metal and alloy 556 weld metal.

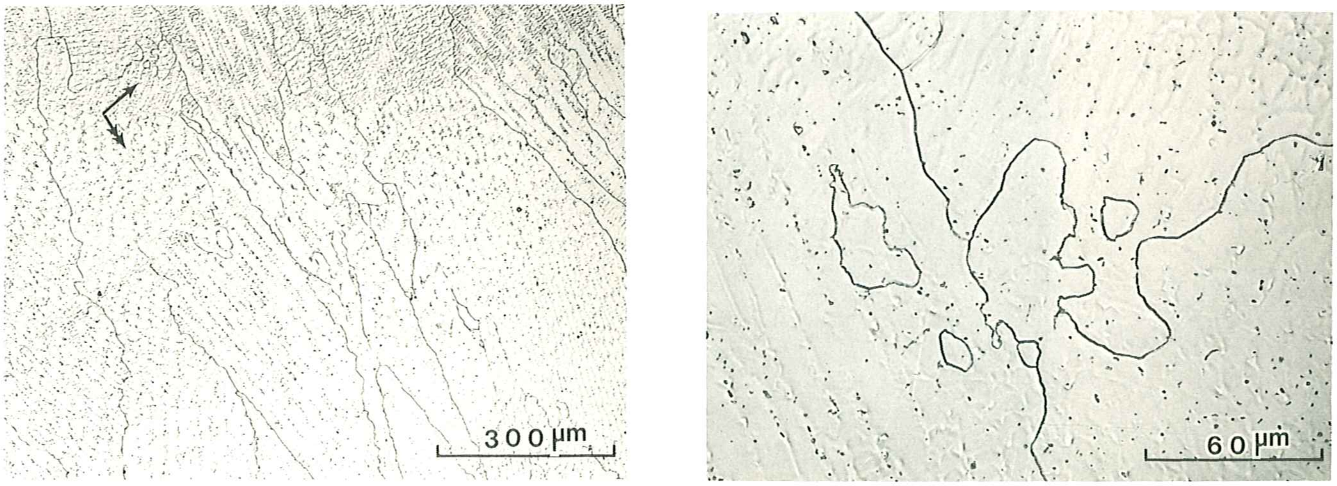

FIGURE 8: Alloy 556 weld metal microstructure. Double arrow indicates reheated pass and single arrow indicates subsequent pass.

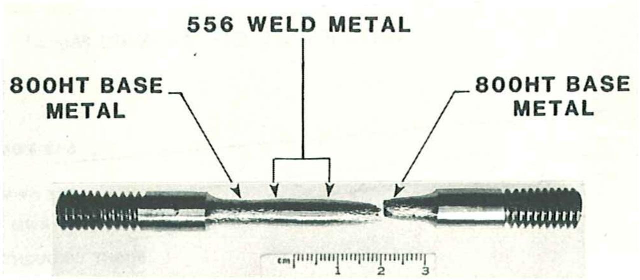

FIGURE 9: Room temperature transverse weldment tensile test specimen. Fracture occurred in alloy 800HT base metal well away from weld zone.

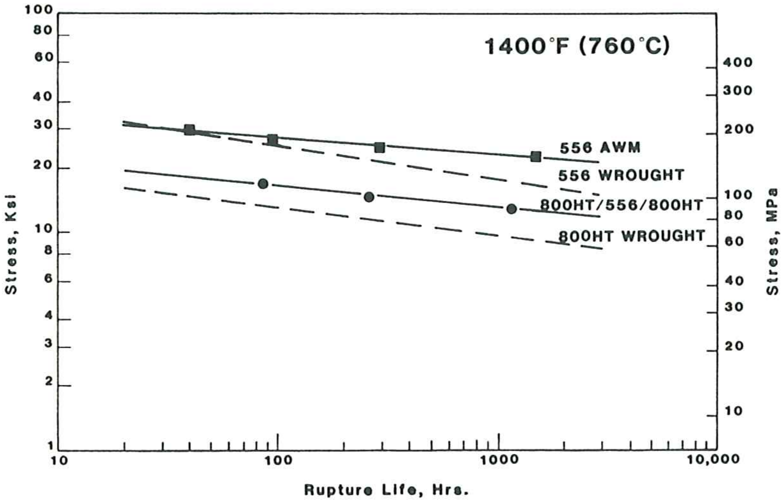

FIGURE 10: Rupture strength at 1400°F (760°C) for alloy 556 all-weld metal (AWM), alloy 556 wrought material, 800HT/556/800HT weldment and alloy 800HT wrought material. Alloy 800HT data from Inco Alloys International, Inc. brochure (Ref. 14).

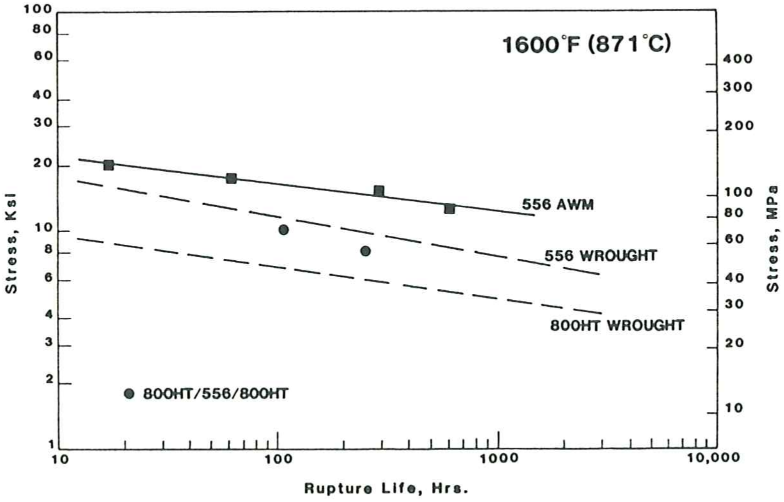

FIGURE 11: Rupture strengths at 1600°F (871°C) for alloy 556 all-weld metal (AWM), alloy 556 wrought material, 800HT/556/800HT weldment and alloy 800HT wrought material. Alloy 800HT data from Inco Alloys International, Inc. brochure (Ref. 14)

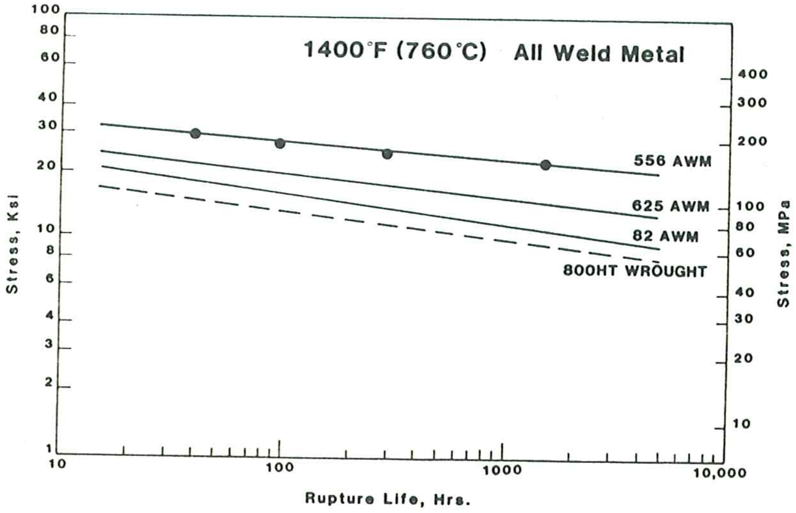

FIGURE 12: Rupture strengths at 1400°F (760°C) for all-weld metal (AWM) specimens of alloys 556, 626 and 82 compared to alloy 800HT wrought material. Alloys 625, 82 and 800HT data from Inco Alloy International, Inc. brochures (Ref. 14 and 15).

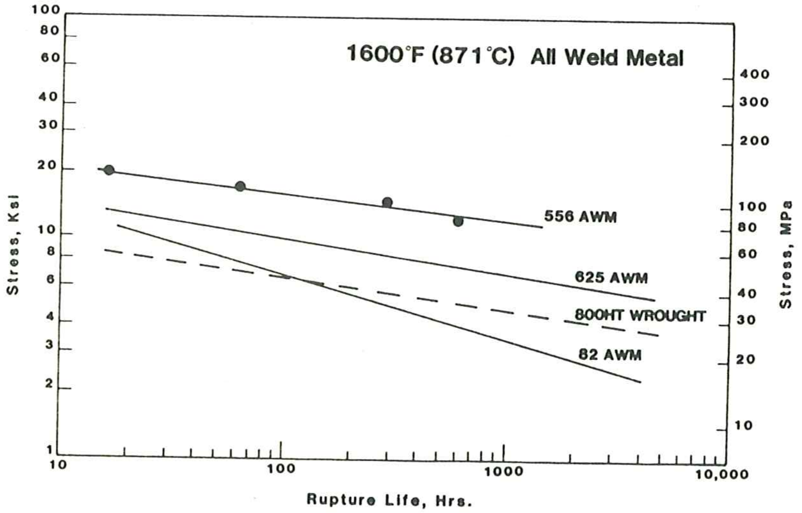

FIGURE 13: Rupture strengths at 1600°F (871°C) for all-weld metal (AWM) specimens of alloys 556, 625 and 82 compared to alloy 800HT wrought material. Alloys 625, 82 and 800HT data from Inco Alloy International, Inc. brochures (Ref. 14 and 15).