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Weldability and Mechanical Property Characterization of Weld Clad Alloy 800H Tubesheet Forging

J. F. King
H. E. McCoy

METALS and CERAMICS
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J. F. King and H. E. McCoy

ABSTRACT

We examined the weldability of an alloy 800H forging that simulates a steam generator tubesheet. Weldability was of concern because a wide range of microstructures was present in this forging. The top and portions of the bottom were weld clad with ERNiCr-3 weld metal to a thickness of 19 mm similar to that anticipated for HTGR steam generators. Examinations of the clad fusion line in various regions revealed no weldability problems except possibly on the bottom portion, which contained large grains and some as-cast structure. A few microfissures were evident in this region, but no excessive hot cracking tendency was observed. The tensile properties in all areas of the clad forging were reasonable and not influenced greatly by the microstructure. The elevated-temperature tests showed strong tendency for fracture in the heat-affected zone of the alloy 800H. Creep failure at 649°C consistently occurred in the heat-affected zone of the alloy 800H, but the creep strength exceeded the expected values for alloy 800H.

INTRODUCTION

We assessed the weldability of an alloy 800H forging that simulates a steam generator tubesheet. This prototypic high-temperature gas-cooled reactor (HTGR) tubesheet forging is the largest known alloy 800H forging. The much larger forgings, 1.6 m in diameter by 0.53 m thick, required for current designs are considered to be one of the longest lead time and most critical components of the steam generators. Approximately one-half of the prototype forging, which was 760 mm in diameter and 500 mm thick, was obtained for use in the weld cladding study. Welding concerns were raised by the wide range of microstructures in this forging. A defect-free clad surface and interface between cladding and base metal are essential for joining the steam generator tubes to the tubesheet by internal bore welding. This study included cladding of the forging surface, metallographic examination of various regions, and tensile and creep tests of the weld metal and the interface.

ALLOY 800H FORGING MATERIAL

A vertical section of an alloy 800H forging was obtained from GA Technologies for weld cladding study at ORNL. This section, Fig. 1, was from a 2500-kg forging, about 760 mm in diameter by 500 mm thick, produced at Cameron Iron Works, Houston, Texas. This forging, heat 54788, was produced on an experimental basis to evaluate large forgings of this alloy. After forging, the piece was solution annealed at 1120°C for 10 h and water quenched. The major evaluation of the forging properties has been conducted at GA Technologies.[1] That evaluation found that the macrostructure of the forging varied greatly, as shown in Fig. 2. The large grains exceeded ASTM 00 in size. The large grain microstructure and the variation of structure throughout the forging prompted the concerns with weldability because weld cladding will be required.

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Fig. 1. Section of alloy 800H forging received at ORNL for weld cladding study. This section is about 460 mm thick by 740 mm wide.

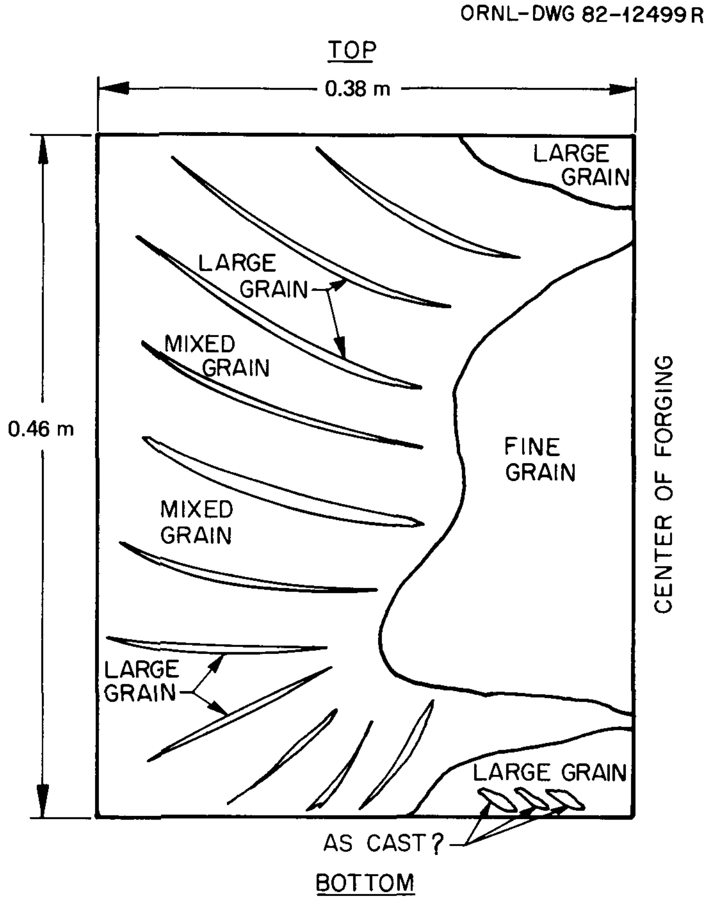

Fig. 2. The macrostructure of the forging varied greatly in examinations made at GA Technologies Inc.

WELD CLADDING OF FORGING SURFACE

Current designs for using large alloy 800H forgings as superheater tubesheets require that the surface be clad with ERNiCr-3 weld metal. This layer must be relatively defect-free because the alloy 800H superheater tubing is joined to the tubesheet by internal-bore welding in this material as shown in Fig. 3. Oxide inclusions in the cladding layer or zones of hot cracking at the cladding-to-base-metal interface could lead to failures because of the relatively low residual thicknesses. To investigate the weldability of this forging surface and determine the cladding mechanical properties, we clad the top surface.

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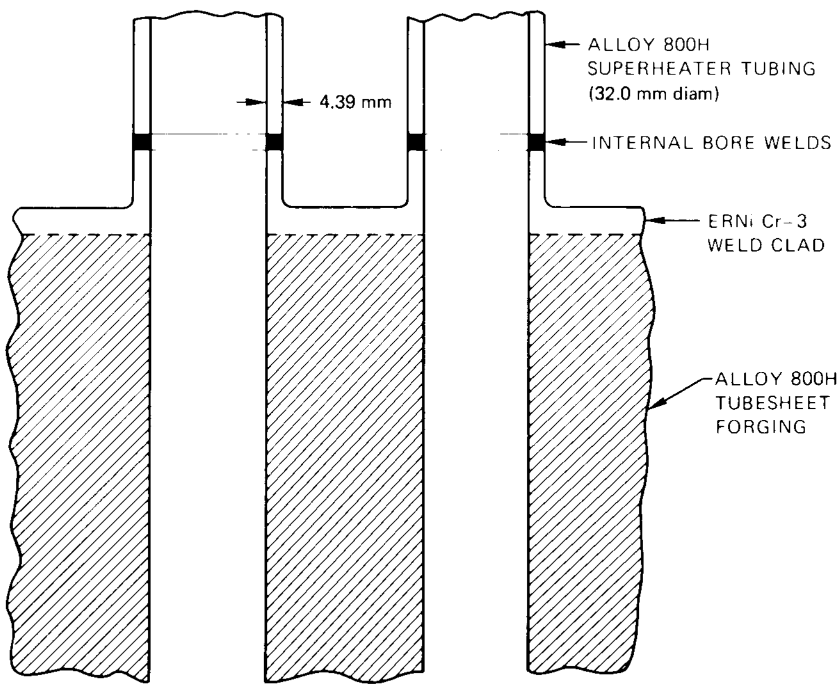

Fig. 3. Weld cladding of the superheater tubesheet forging is required to provide material for joining tubes to the tubesheet by internal bore welding.

Weld cladding was accomplished by the hot-wire gas tungsten arc process shown in Fig. 4. The clad deposit was AWS specification ERNiCr-3. This filler metal has a nominal composition of 67% Ni—20% Cr—3% Mn—3% Fe—2.5% Nb. A surface view of the completed first layer is shown in Fig. 5. Seven layers were deposited to complete the clad to a depth of 19 mm. Welding parameters for this cladding are listed in Table 1. After welding, the top of the forging with the weld clad was removed by sawing. An additional area on the bottom, identified in Fig. 2 as having large grains and as-cast structure, was weld clad later by the same technique and welding procedure. The top layer and this localized bottom section were used for the subsequent studies.

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Fig. 4. The hot-wire gas tungsten arc welding process being used to clad the alloy 800H forging section.

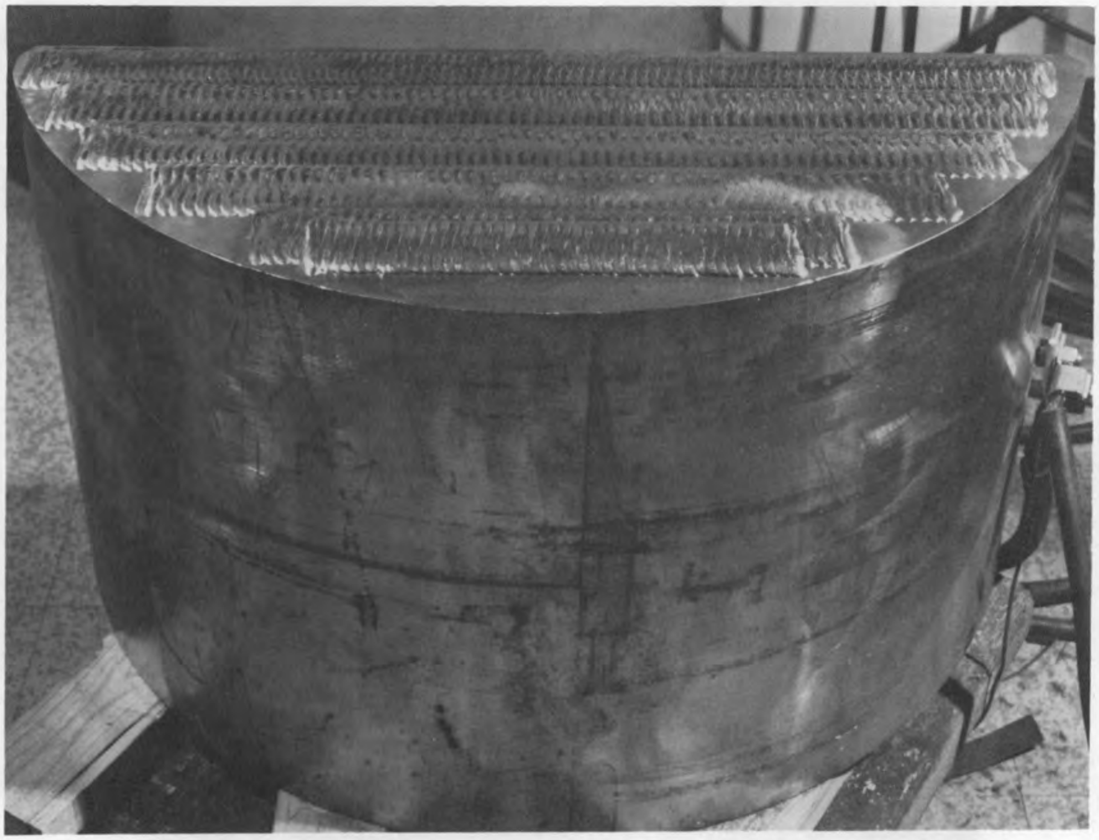

Fig. 5. Surface view of the first layer of weld clad on alloy 800H forging. Seven layers were required to complete the cladding.

Table 1. Welding parameters for cladding alloy 800H forging

GTA welding torch	
Current, A	250 to 375, dc straight polarity
Voltage, V	13 to 14
Travel speed, mm/s	0.6 to 0.85
Shielding gas	75% He—25% Ar
Hot-wire filler addition	
Current, A	80, ac
Wire feed rate, mm/s	85
Wire diameter, mm	1.14
Oscillation	
Width, mm	51
Dwell time, s	2
Frequency, cycles/min	7

RESULTS OF CLAD FORGING EXAMINATION

The clad forging was examined to determine if weldability problems existed and to determine the tensile and creep properties of the weld clad. From visual examination and observations made during the weld cladding, no weldability problems were apparent. Side-bend test specimens were prepared and tested as shown in Fig. 6. These specimens contained one-half forging base material and one-half weld cladding. After bending, the specimens contained no gross defects, and the fusion line had good ductility.

Y-184599

Fig. 6. Side-bend test specimens containing weld metal cladding and forging base material revealed no gross defects and good ductility at the fusion line.

Twelve metallographic specimens were prepared from the forging top clad surface. These were selected to show the wide range of microstructures in the forging. No fusion line defects or evidence of hot cracking was found in any of the zones of different microstructure. Figure 7 is a typical photomicrograph of a fine-grained region of the forging with the ERNiCr-3 weld clad, and Fig. 8 is from a typical coarse-grained region. The variable microstructures present at the forging top surface apparently had no detrimental effect on the weldability.

The metallographic examination of the clad bottom section of the forging, shown in Fig. 2 as having large as-cast grain structure, revealed different results. Six metallographic specimens were examined from the center of this region. Most of the fusion line regions examined were sound and similar to the top section. Figure 9 shows this fusion line with a zone of the as-cast structure in the large-grained base material.

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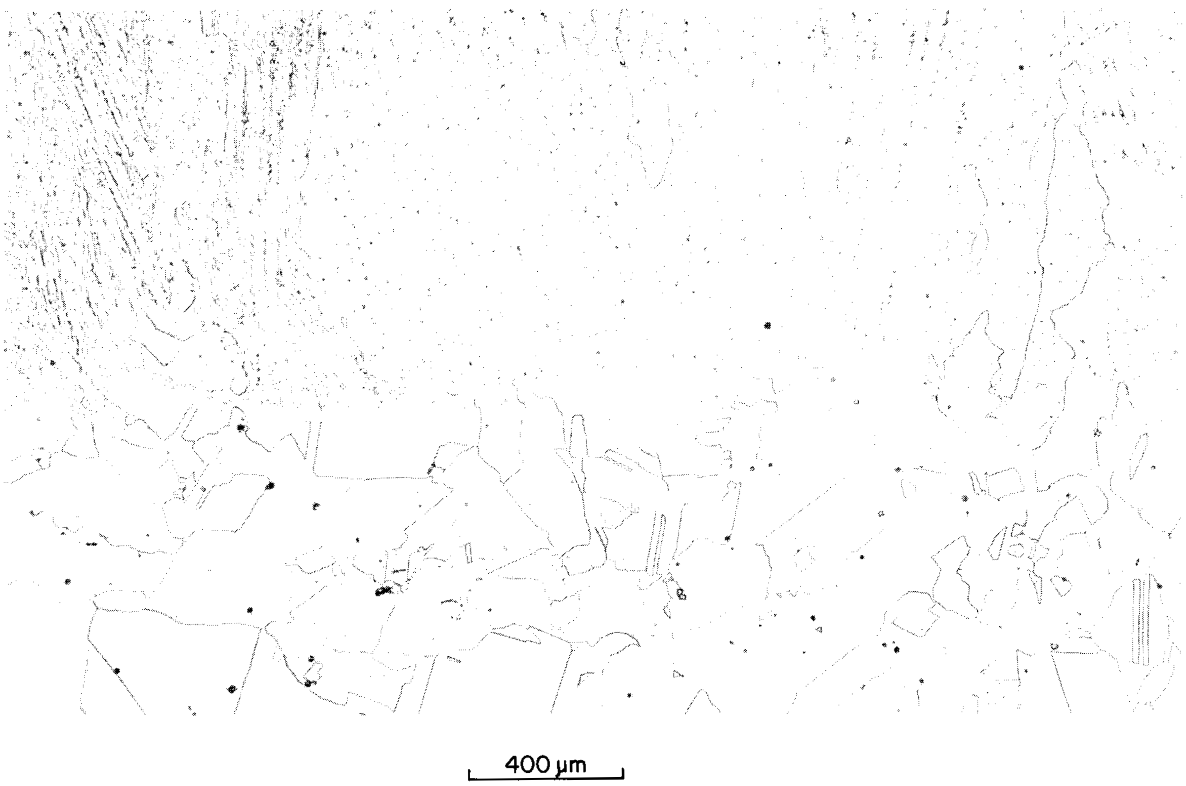

Fig. 7. Typical weld clad fusion line from a fine-grained region of the alloy 800H forging.

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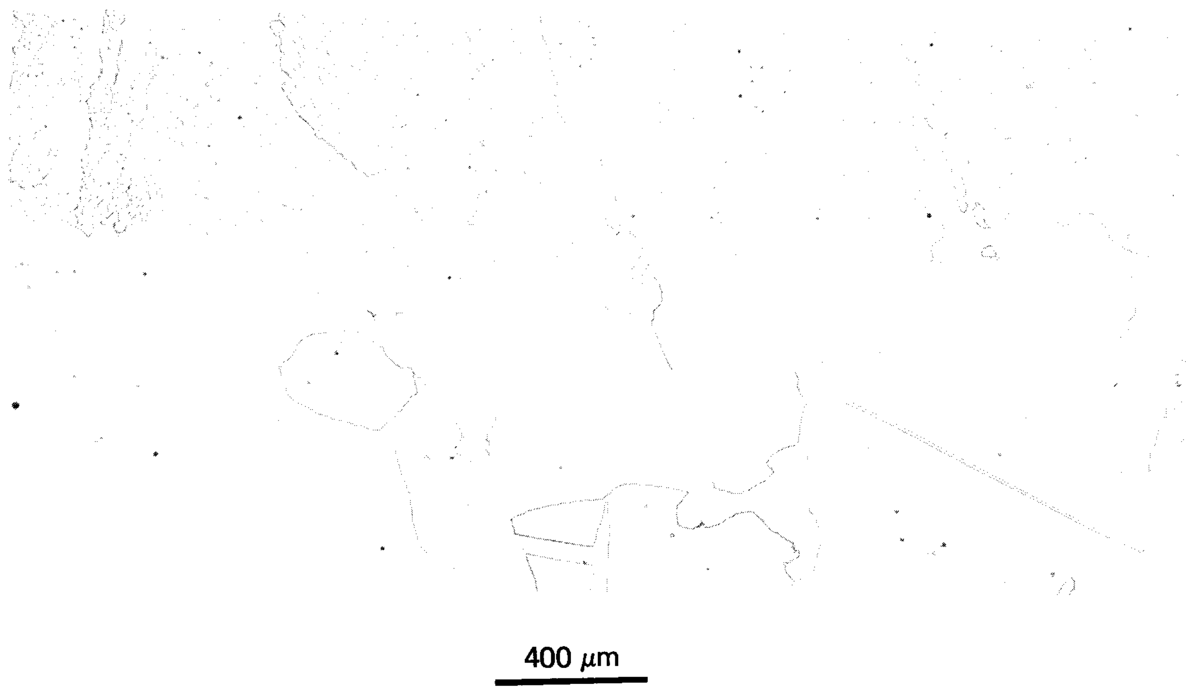

Fig. 8. Typical weld clad from a coarse-grained region of the alloy 800H forging.

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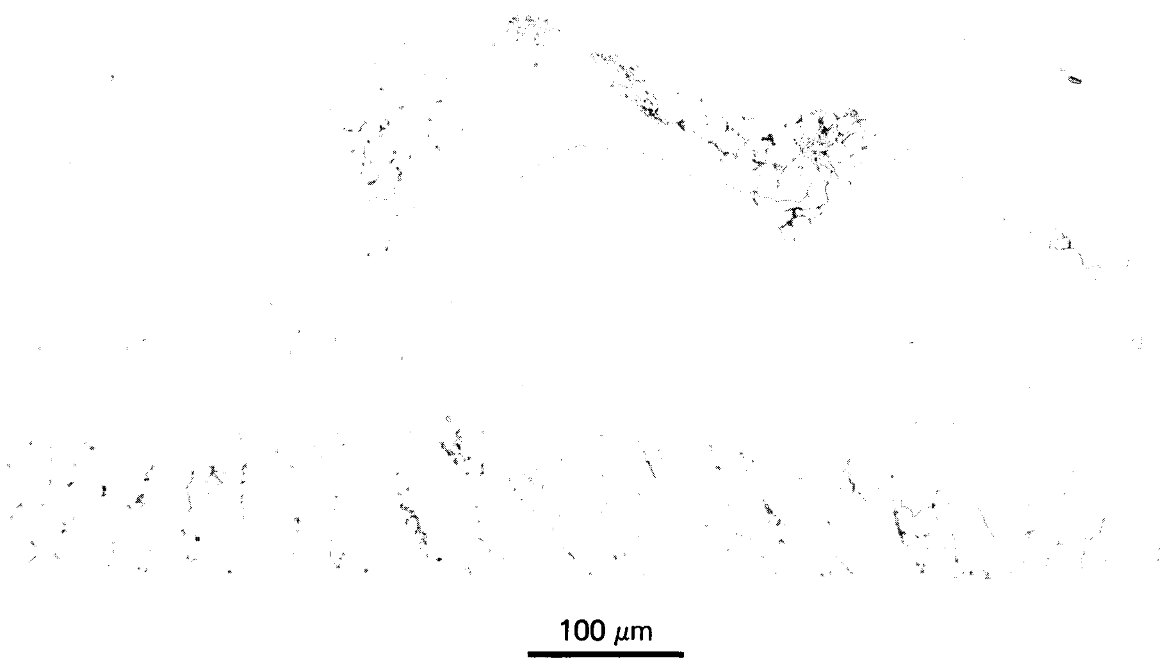

Fig. 9. Large-grained region containing as-cast structure from weld-clad bottom section of forging.

Microprobe examination of this as-cast zone revealed a high concentration of titanium. Heat-affected zone (HAZ) hot cracking in alloy 800 weldments has been associated with localized titanium enrichment.[2] A few fissures were found at or near the fusion line in the HAZ of the weld-clad bottom section, but these were not conclusively determined to be caused by the as-cast structure. Figures 10 and 11 show two of the areas containing hot cracks. These cracks could cause problems in a clad tubesheet.

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Fig. 10. Heat-affected zone hot crack found in the large-grained region near center of forging bottom.

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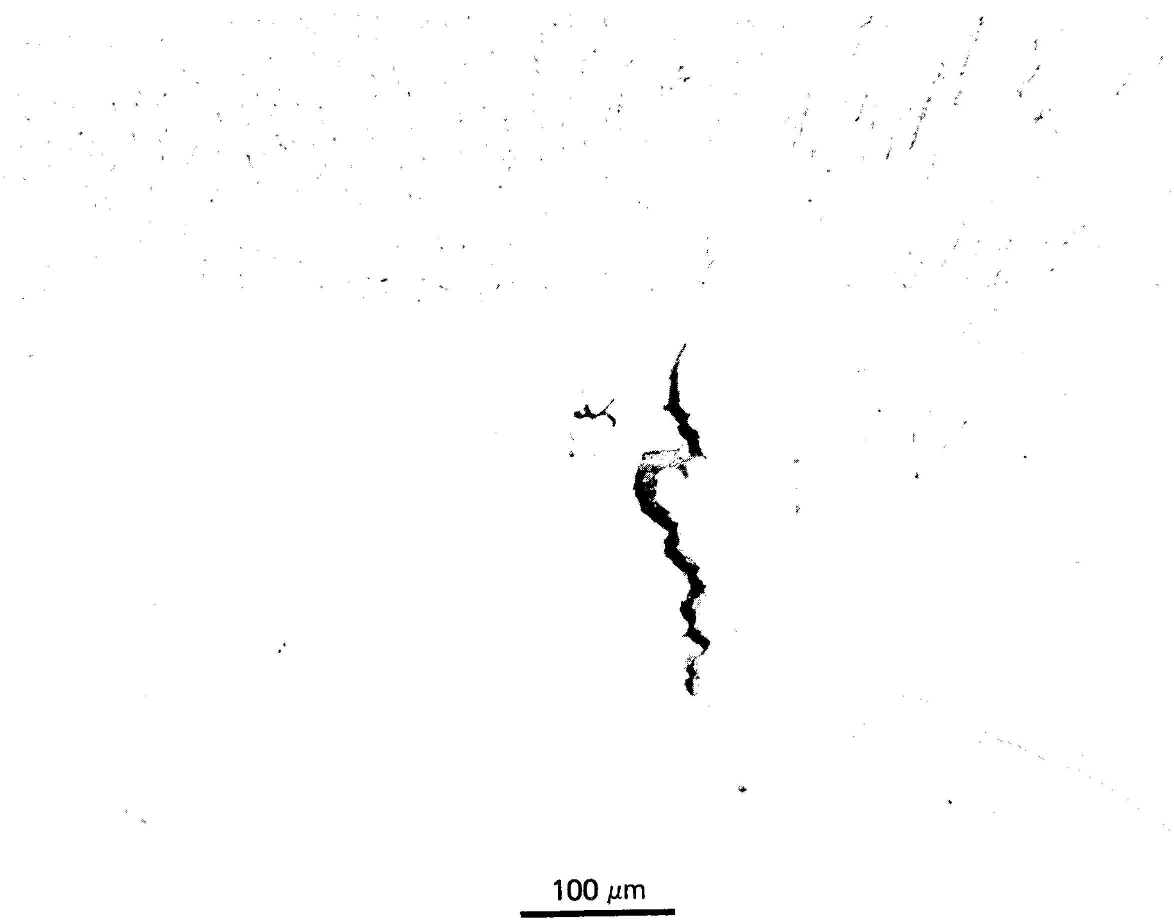

Fig. 11. Heat-affected zone hot crack from weld-clad forging bottom.

TENSILE TEST RESULTS

Test samples were taken in the manner shown in Fig. 12. The specimens designated "WT" and "WL" were entirely of weld metal, and the test sections were 6.35 mm in diameter by 25.4 mm long (0.250 × 1.000 in.). These two orientations are orthogonal to each other and are in the plane of the weld overlay. Samples were also taken with their axes perpendicular to the plane of the overlay and machined so that their gage sections consisted of only weld metal (WV), only alloy 800H base metal (B), and the weld interface including the fusion line and small portions of weld metal and alloy 800H (I). These samples had gage sections 6.35 mm in diameter by 12.7 mm long (0.250 × 0.500 in.)

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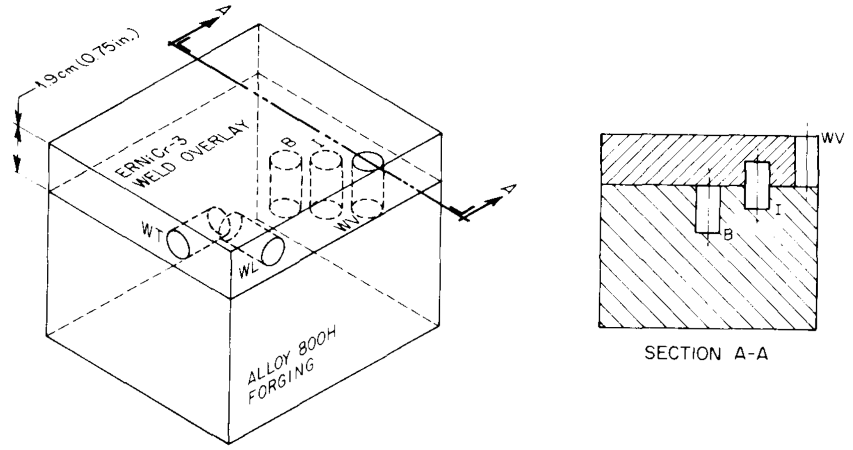

Fig. 12. Orientations of test samples from alloy 800H forging with about 19-mm weld overlay of ERNiCr-3. The abbreviations used are more fully described as WT = tranverse sample of weld metal, WL = longitudinal sample of weld metal, WV = vertical sample of weld metal, I = sample across weld overlay—base metal interface, and B = sample totally of alloy 800H base metal.

The results of tensile tests on these samples are summarized in Table 2. The strength parameters (yield and ultimate tensile strengths) are compared in Fig. 13 with those reported in Huntington Alloys literature for alloy 800H base metal and deposited ERNiCr-3 weld metal.[3] Although the Huntington Alloys data indicate that the ERNiCr-3 weld metal is considerably stronger than alloy 800H, our test results did not show much variation between the properties of the two materials. Our alloy 800H appears to be stronger than the vendor's data indicates, and our deposited ERNiCr-3, weaker. The vendor's data for alloy 800H are for annealed 20.7-mm-thick (0.813-in.) plate, and our material was a rather large forging with very large grain size. The larger grain size of our material may account for the higher strength. The vendor's data for ERNiCr-3 are for weld deposits made in welding alloy 800H. Standard weld configurations would have involved considerably more intermixing between weld and base metals than would a weld overlay 19 mm (0.75 in.) thick, so it is not surprising that the strengths do not agree exactly.

Table 2. Tensile properties of alloy 800H–ERNiCr-3 sample

Sample and orientation[a]		Test temperature (°C)	Yield stress		Ultimate tensile stress		Elongation (%)		Fracture[b] location	Reduction of area (%) at	
			(MPa)	(ksi)	(MPa)	(ksi)	Uniform	Total		Fracture	Interface[c]
T-1	WT	25	332	48.1	608	88.2	65.0	67.4		59.8	
L-1	WL	25	354	51.3	612	88.8	55.0	59.4		61.3	
S-2	WV	25	300	43.5	579	84.0	62.0	80.0		68.0	
S-4	B	25	314	45.5	558	81.0	47.3	59.4		60.8	
S-1	I	25	332	48.2	565	82.0	51.3	66.0	I	67.3	
S-9	I	25	348	50.5	567	82.2	51.7	63.4		63.4	23.8
S-15	I	25	337	48.9	566	82.1	54.8	63.8		58.4	22.8
S-21	I	25	337	48.9	574	83.2	56.7	67.7		59.7	25.7
S-28	I	25	318	46.1	569	82.6	55.1	70.1		67.3	32.1
S-33	I	25	339	49.1	576	83.5	52.4	66.6		63.8	28.8
T-2	WT	427	270	39.1	505	73.3	66.0	72.6		55.6	
L-2	WL	427	254	36.8	519	75.3	60.2	63.7		50.7	
T-3	WT	538	257	37.3	474	68.8	65.5	70.8		61.8	
L-3	WL	538	265	38.5	487	70.6	55.0	61.7		56.8	
S-5	WV	538	225	32.6	456	66.2		82.4		79.1	
S-12	B	538	238	34.5	448	65.0		63.4		51.3	
S-3	I	538	241	35.0	425	61.6		44.2	I	47.0	
S-29	I	538	241	34.9	454	65.8		62.8	I	58.0	
S-35	I	538	266	38.6	474	68.7		66.4	I	54.4	
T-4	WT	649	205	29.8	390	56.6	56.1	56.1		59.5	
L-4	WL	649	208	30.2	383	55.5	64.8	73.8		56.5	
S-27	WV	649	214	31.0	412	59.7	60.0	90.4		70.1	
S-14	B	649	245	35.6	368	53.4	38.0	45.2		42.7	
S-6	I	649	273	39.6	415	60.2	40.4	48.4	I	46.7	
S-10	I	649	244	35.4	412	59.7	48.6	60.6		45.2	29.9
S-17	I	649	235	34.1	406	58.9	45.4	53.4		40.5	23.8
S-22	I	649	243	35.2	412	59.7	48.0	58.0	I	50.8	
S-30	I	649	231	33.5	414	60.0	43.2	49.2	I	35.2	
S-36	I	649	245	35.6	414	60.1	41.0	48.1	I	43.3	

[a]See Fig. 12 for definition of symbols. Samples designated WT and WL had a gage length of 25.4 mm (1.000 in.) and were deformed at a rate of 0.2 m/s. Samples designated WV, B, and I had a gage length of 12.7 mm (0.500 in.) and were deformed at a rate of 0.2 m/s.

[b]"I" denotes that failure occurred at interface between weld metal and base metal.

[c]If the sample contained a weld-base-metal interface (orientation "I") and failure did not occur at the interface, the value in this column denotes the reduction of area at the interface.

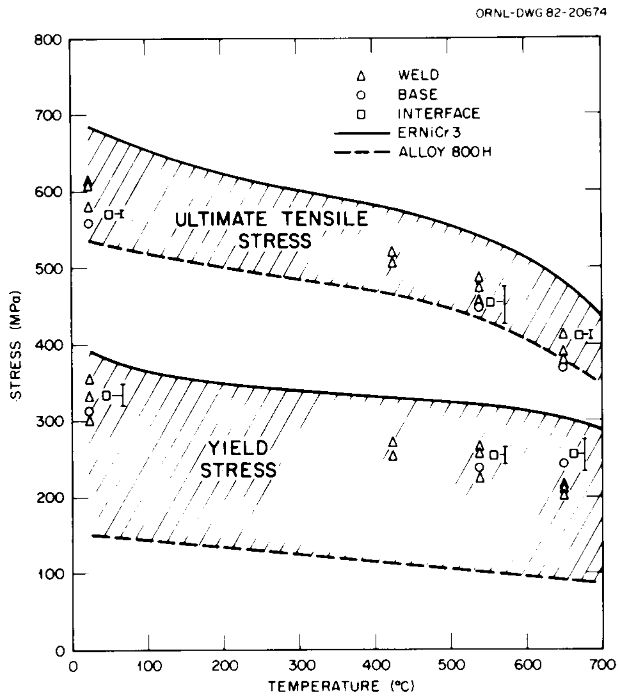

Fig. 13. Comparison of tensile properties of alloy 800H-ERNiCr-3 weldment samples with those for alloy 800H base metal and ERNiCr-3 weld metal from manufacturer's literature.

The elongation and reduction of area values in Table 2 show that the base and weld metals were ductile over the entire range of test temperatures. One interesting observation was that several of the samples failed at the fusion line or alloy 800H–ERNiCr-3 interface (noted "I"). At a test temperature of 25°C, six samples had a fusion line in the gage length, and failure occurred at the fusion line in one sample. At 538°C, three samples had fusion lines in the gage length, and all three samples failed at the fusion line. At 649°C, six samples had fusion lines in the gage length, and failure occurred at this location in four samples. Thus, there may be a weakness at the fusion line. When failure did not occur at the fusion line, the diameter at the fusion line was measured 'nd the reduction of area calculated (right-hand column, Table 2). Considerable deformation occurred at the fusion line, even when failure occurred elsewhere.

The various samples tested came from numerous locations in the fabricated part and represent obvious differences in grain size of the alloy 800H and other more subtle differences in working and other variables. The spread in experimental results is quite small, indicating that these variables had little effect on the properties.

CREEP TEST RESULTS

Samples having the same geometry and locations within the forging as the tensile specimens were creep tested. The tests were run in air at 649°C, and the results are summarized in Table 3. The stress-rupture data are shown in Fig. 14. The three lines in this plot are as follows: (1) the expected minimum values for alloy 800H from Code Case N-47 of the *ASME Boiler and Pressure Vessel Code*,[4] (2) the expected average values for alloy 800H from Huntington Alloys publications,[3] and (3) typical values for ERNiCr-3 interpolated from data by Klueh and King.[5] One test specimen, which included a weld-base metal interface in the gage length, likely contained a flaw, since it ruptured in an unusually short time (test 23353). The results for all other specimens exceeded the manufacturer's average strength requirement.

Minimum creep rate data are plotted in Fig. 15 for the tests. Lines are shown in this figure for the expected average values for alloy 800H based on manufacturer's literature[3] and for typical values for ERNiCr-3 based on work by Klueh and King.[5] All the results meet or exceed the expected average values for alloy 800H, and most of the results meet or exceed the properties measured for ERNiCr-3. The single specimen of alloy 800H base metal appears unusually strong on the basis of minimum creep rate. This is likely real for the forging and is due to the very large grain size. However, the fracture strain of this sample was quite low, and the test sample may have contained a flaw.

The sample from test 23332 (649°C, 241 MPa) was an interface sample, and the failure location in this sample was typical of that for other samples with an interface in the gage section between base metal and weld overlay. This sample was examined metallographically, and typical photomicrographs are shown in Figs. 16 and 17. The fracture occurred in the HAZ of the alloy 800H. The grain size of the alloy 800H was very

Table 3. Creep properties of alloy 800H—ERNiCr-3 samples in air at 649°C

Test	Sample[a] orientation	Stress (MPa)	Stress (ksi)	Time (h) to indicated strain: 1%	2%	5%	Tertiary creep	Rupture	Minimum creep rate (h^{-1})	Strain (%): Loading	Strain (%): Creep	Reduction of area (%)
23356	I	207	30	110	470	1600	1430	1695	2.2E-5	0.5	11.8	19.2
23353	I	207	30					27.6	1.8E-4	0.4	6.5	21.8
23612	WV	207	30	45	100	320		1070	1.1E-4	0.3	23.2	19.7
23613	WV	207	30	60	135	510		930	8.2E-5	0.3	19.1	27.2
23351	I	241	35	10	38	132	98	141	2.2E-4	0.9	12.3	6.7
23332	I	241	35	18	40		135	154	2.5E-4	0.6	11.8	14.1
23590	I	241	35	8	32	110	102	126	3.2E-4	1.0	12.4	15.9
23604	I	241	35	17	52	110	90	139	2.8E-4	0.9	16.4	20.2
23647	I	241	35	20	60		149	163	2.1E-4	0.7	13.4	10.2
23657	I	241	35	7	28	111	111	139	3.4E-4	0.9	17.5	18.3
23694[b]	I	241	35	3	35	138	153	157	3.0E-4		27.4	25.2
23605[b]	I	241	35	2	17	105	126	148	3.1E-4	12.6	28.6	25.6
23608[c]	I	241	35	3	8	38	102	122	7.1E-4	1.8	24.5	34.6
23611[c]	I	241	35	3	8	40	143	155	4.9E-4	1.5	20.6	25.0
23334	B	241	35					1370	1.1E-6	0.5	0.4	0.5
23598	WV	241	35	20	53	210	660	802	1.4E-4	0.6	26.8	17.0
23345	WV	241	35	15	45	180	660	1032	1.7E-4	0.6	40.9	40.3
23618	WV	241	35	12	25	80	410	420	3.5E-4	1.0	21.1	23.7
23772	WV	241	35	15	33	70		307	4.1E-4	0.8	17.6	26.0

[a]See Fig. 12 for definition of symbols. Samples designated WV, B, and I had a gage length of 12.7 mm (0.500 in.)

[b]Annealed 1 h at 1177°C before testing.

[c]Annealed 2 h at 788°C before testing.

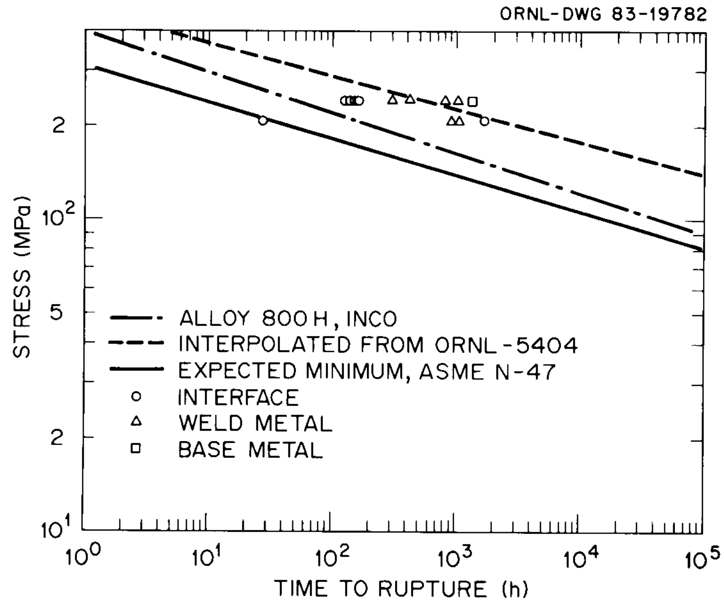

Fig. 14. Stress-rupture properties at 649°C of samples from alloy 800H forging with ERNiCr-3 overlay. Compared with properties of alloy 800H base metal from manufacturer's literature and Code Case N-47 and of ERNiCr-3 from ORNL-5404.

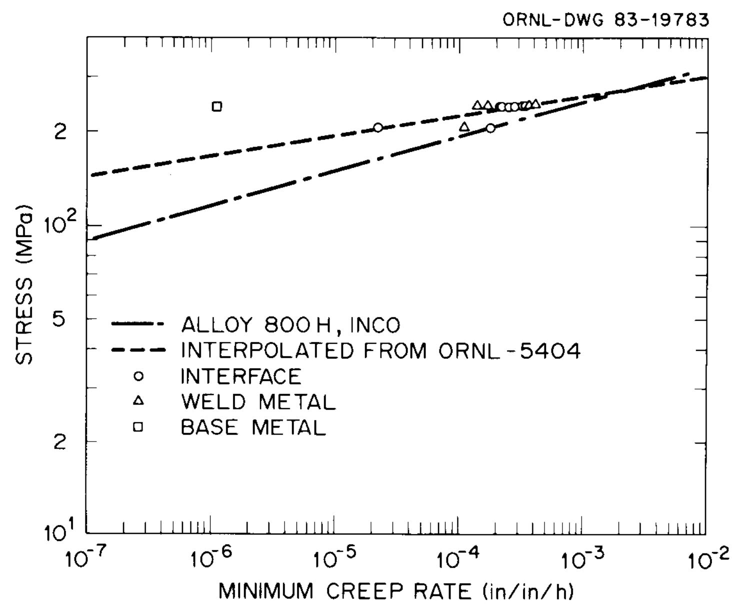

Fig. 15. Minimum creep rate at 649°C of samples from alloy 800H forging with ERNiCr-3 overlay. Compared with properties of alloy 800H from manufacturer's literature and of ERNiCr-3 from ORNL-5404.

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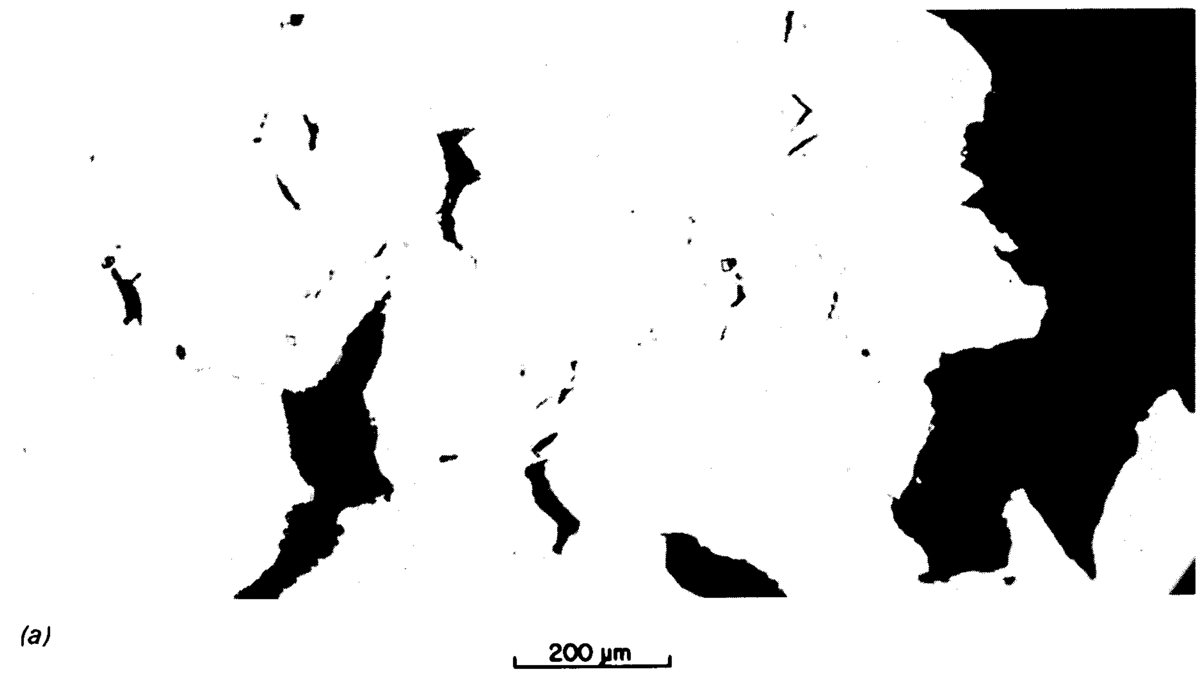
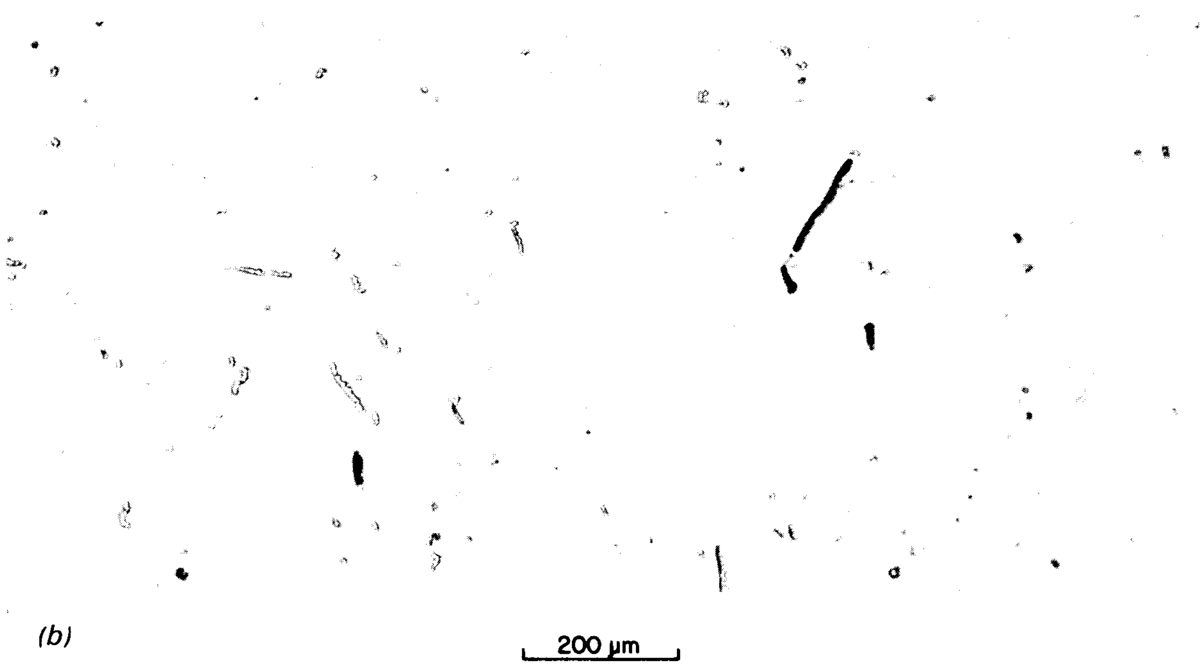


(a)

Y-192009



(b)

Fig. 16. Fractured specimen from test 23332 (649°C, 241 MPa) as polished. (*a*) Fracture in alloy 800H. (*b*) Typical microstructure of deposited ERNiCr-3.

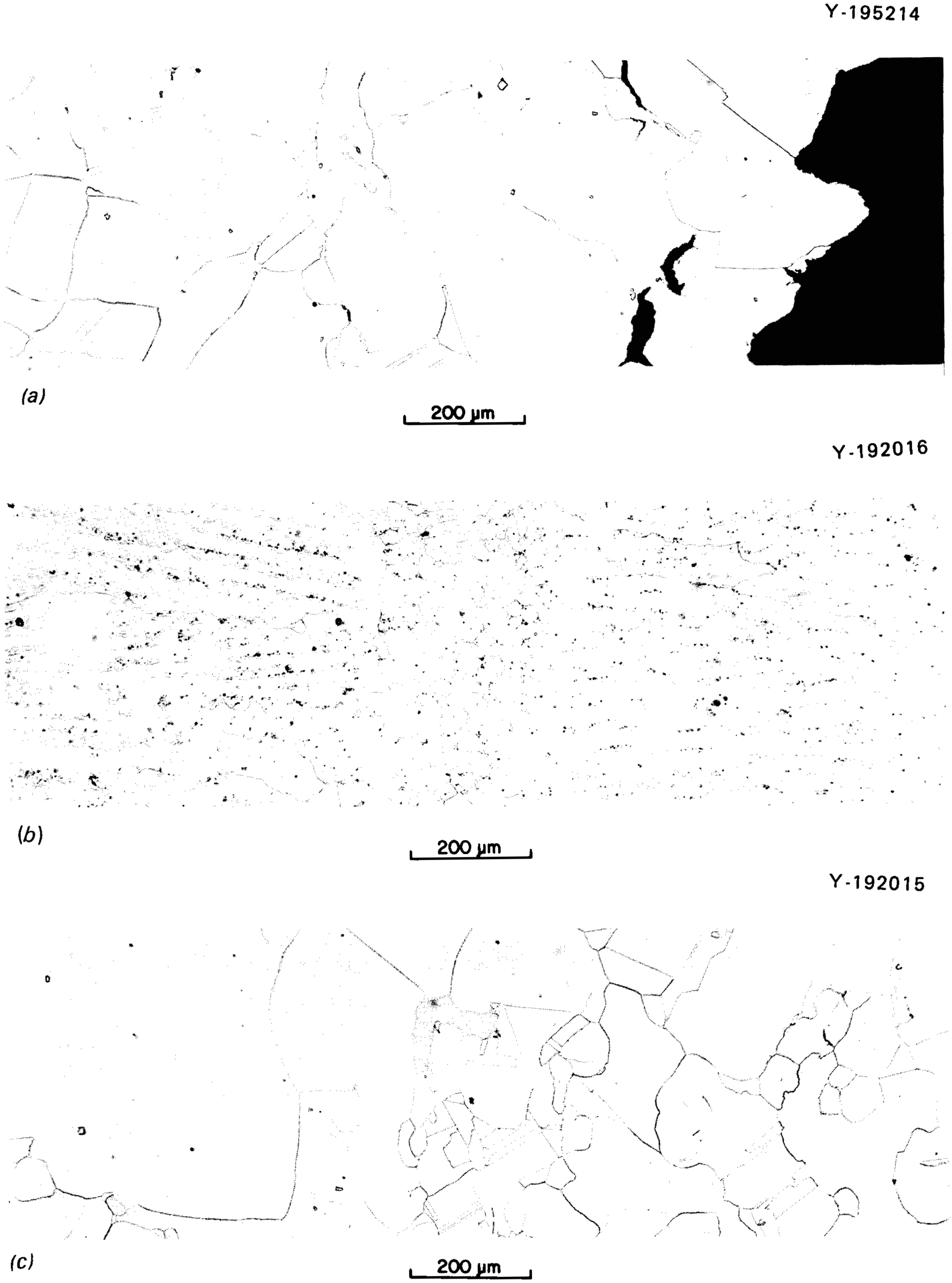


Fig. 17. Fractured specimen from test 23332 (649°C, 241 MPa) etched. (*a*) Fracture in alloy 800H. (*b*) Typical microstructure of deposited ERNiCr-3. (*c*) Typical microstructure of alloy 800H.

irregular, with regions having coarse and fine grain sizes. The weld deposit had a cellular dendritic structure with some thin layers of fine-grained material between adjacent passes.

CONCLUSIONS

The following conclusions are based on these studies.

1. The variable microstructure of the alloy 800H forging did not have a significant effect on its weldability related to weld cladding, with the exception that sections from the forging bottom, which contained large grains and some as-cast structure, did contain some microfissures after cladding.
2. A more uniform microstructure is desirable for weld cladding.
3. The test results indicate that tensile properties of all areas of the fabricated part are reasonable. The strength parameters are above minimum requirements for alloy 800H, the weaker component of the fabricated unit.
4. Fracture strains are high in all areas, indicating a lack of embrittlement due to the weld overlay process.
5. The tensile properties appear quite acceptable, but there is a strong tendency at elevated temperatures for failure to occur at the fusion line.
6. Fabrication variables that affected grain size and possibly other properties had no detectable influence on the tensile properties at various locations in the forging.
7. Samples tested under creep conditions failed in the HAZ of the base metal. The creep strength and stress-rupture properties of base metal, interface, and weld metal samples exceeded the expected average properties of alloy 800H.

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