CONF-770524--3

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ELEVATED-TEMPERATURE FATIGUE CHARACTERIZATION OF TRANSITION JOINT WELD METAL AND COMPOSITE MATERIAL IN SUPPORT OF LMFBR STEAM GENERATOR DEVELOPMENT

C. R. Brinkman[1], J. P. Strizak[2] and J. F. King[3]

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ABSTRACT

Piping systems in Liquid Metal Fast Breeder Reactor (LMFBR) plants will require transition joint weldments between austenitic and ferritic materials. Specifically, annealed 2 1/4 Cr-1 Mo steel will be welded with ERNiCr-3 by the hot wire automatic gas tungsten-arc process. These weldments will see elevated-temperature service for periods of up to 30 years and, accordingly, prototypic weldments will require extensive mechanical property characterization. The objective of this effort was to define the strain-controlled low-cycle fatigue behavior of as-deposited and stress-relieved ERNiCr-3 weld metal and to develop test methods for establishing the cylic behavior of heat-affected zone (HAZ) material. Low cycle fatigue and the cyclic stress-strain response for ERNiCr-3 were established over the temperature range from 295 to 866 K. A number of low-cycle fatigue tests of hourglass-shaped specimens demonstrated that the low-cycle fatigue behavior of HAZ material adjacent to the fusion line could be characterized.

KEY WORDS: fatigue (materials), high-temperature fatigue, low-alloy steels, Inconel, stress cycle, weld metal.

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*Research sponsored by the Energy Research and Development Administration under contract with the Union Carbide Corporation.

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Current plans call for construction of the Clinch River Breeder Reactor Plant (CRBRP) steam generator system primarily out of annealed 2 1/4 Cr-1 Mo steel [1]. Many of the steam generator piping components will require transition weld joints to connect the ferritic material to austenitic piping leading to other components within the system. Pipe diameters will range from 50 mm to as large as 660 mm, with design temperatures as high as about 790 K [2,3]. A diagram showing the cross section of CRBRP transition joints between 2 1/4 Cr-1 Mo steel and type 316 stainless steel is shown in Fig. 1. The weld filler metals shown are ERNiCr-3 (67 Ni—20 Cr—2.5 to 3.5 Mn—2.5 Nb + Ta — 0.10 C, wt %) and 16-8-2 (16 Cr—8 Ni—2 Mo balance Fe, wt %) stainless steel. One of the requirements for maintaining integrity of a transition joint subject to loading from static and dynamic thermal stresses is a gradual transition in coefficient of thermal expansion across the weld joint, as shown in Fig. 1. Hence, alloy 800H is added as a spool piece.

Transition joints between 2 1/4 Cr-1 Mo ferritic steel and type 316 stainless steel have been successfully used in commercial fossil-fired power plants subject to elevated temperatures for many years. However, incidences have been reported of failure resulting from primarily fatigue and creep in combination with surface oxidation occurring in the ferritic material adjacent to the fusion line, and metallurgical changes occurring within the heat-affected-zone (HAZ) of the ferritic material [3,4]. While we believe that the operating temperatures of the piping transition joints within CRBRP will be low enough to preclude environmentally induced changes within the critical HAZ areas of the 2 1/4 Cr-1 Mo piping, the possibility of damaging mechanisms occurring over a design lifetime of 30 years cannot be totally discounted. Accordingly, systematic programs are under way at Oak Ridge National Laboratory (ORNL) and elsewhere to develop the mechanical properties of base, weld filler and composite material properties. This program calls for the initial testing of weldment and base materials using essentially small specimens for tensile, creep, fatigue, and creep-fatigue evaluations. However, testing of full scale pipe transition joints is planned. The objective of this paper is to report continuous cycling strain-controlled fatigue and cyclic stress-strain data and discuss results obtained from ERNiCr-3 all-weld metal specimens taken from prototypic as-fabricated and stress-relieved weldments. Further, interim results of continuous cycle fatigue tests will be reported that were obtained with composite specimens taken from the HAZ in the 2 1/4 Cr-1 Mo steel side of the weldment, since this is the region currently considered to be most important in terms of resistance to environmental degradation.

PROCEDURE

Material

Plates of 19-mm-thick annealed 2 1/4 Cr-1 Mo steel (ASME SA-387 Grade D) containing 0.11% C were joined by multiple pass welding employing the automatic gas tungsten-arc process using either cold-or hot-wire ERNiCr-3 filler additions. The hot-wire process is superior to cold-wire welding for this application since it minimizes dilution and allows higher deposition rates. These weldments were prepared with a 30°-included-angle V-groove joint geometry with a 32-mm root opening and a backing strip. Typically, filling the joint required 40 weld passes with the cold-wire process and 16 to 18 with the hot-wire process. The welded plates were radiographed and when found to be defect-free were stress relieved for 1 hr at 1005 K. A typical composition (wt %) of the weld metal was found to be as follows.

Cr	Fe	Mn	Nb	Ti	Ni
18	1.8	3.0	2.3	0.3	balance

Greater concentrations of iron were found in weld metal areas adjacent to the fusion line, indicating some dilution. Figure 2 shows the microstructure and associated hardness values of a typical multipass weldment fabricated in the above manner. As can be seen by the hardness profile the ERNiCr-3 deposit is harder than the annealed 2 1/4 Cr-1 Mo steel. The HAZ consists of a tempered bainite structure caused by the cooling cycle following welding. The structure variation across the weld metal through the HAZ into the annealed 2 1/4 Cr-1 Mo steel is quite complicated because of compositional differences, varying amounts of residual cold work induced during multipass welding, and the variation in response to heat treatment.

After the weldments were stress relieved, both fatigue and tensile specimens were taken from essentially the central sections of the weld metal such that the uniform gage lengths consisted entirely of weld metal. The tensile specimens (3.18-mm-diam and 28.6-mm-long gage section) were fabricated with a longitudinal orientation (major axis parallel to the fusion line), while the uniform-gage fatigue specimens (6.35-mm-diam and 10.16-mm-long) were fabricated with both transverse and longitudinal orientations. In addition, hourglass-shaped (zero gage length) specimens (minimum diameter was 5.08-mm with a radius-to-diameter ratio of 6) were also fabricated with a transverse orientation with respect to the fusion line such that the minimum diameter was located within the HAZ. This was done so as to allow strain-controlled fatigue testing of HAZ material adjacent to the fusion line. Final buffing of all specimens was done longitudinally so as to remove all circumferential grinding marks and leave a 0.20–0.28 μm (8–11 μ in.)

surface finish. Additional information concerning specimen preparation can be found elsewhere [5]. Before testing all specimens were radiographed and rejected if defects were found.

Testing Procedure

All the fatigue tests were conducted in air with induction heating at a strain rate of 4×10^{-3} s^{-1} in axial strain control. Strain was measured with a diametral extensometer for the hourglass HAZ specimens and with an axial extensometer (9.53-mm gage length) used for the uniform-gage specimens. The minimum diameter of the hourglass HAZ specimens, and hence the point of contact of the diametral extensometer, was located 1 to 2 mm from the weld fusion line. Additional details concerning test methods can be found elsewhere [5].

RESULTS

Results of tensile tests conducted on all-weld-metal specimens are plotted as a function of temperature and compared with trend lines for annealed [6] and normalized-and-tempered [7] 2 1/4 Cr-1 Mo steel in Fig. 3. The trend lines for normalized-and-tempered material are only indicative of the tensile properties of the material adjacent to the fusion line because of both the cold work and heat treatment variations shown in Fig. 2. Little difference is apparent between the tensile properties of the hot-and cold-wire weld metal. The yield and ultimate strengths of the weld metal were intermediate between those of the annealed and normalized-and-tempered 2 1/4 Cr-1 Mo steel. Ductilities, as measured by reductions of area, were lower than that of the 2 1/4 Cr-1 Mo steel in either heat treatment.

Results of the strain-controlled fatigue tests are given in Table 1. Cycle life (N_f) was defined to be the number of cycles corresponding to a 20% decrease in the stress range, measured at about half of the estimated cycle life of the specimen. This was necessary since, in some instances, specimen failure (separation into two halves) occurred only after the stress range had decreased to a very low value. Hence, defining failure in this manner provided a uniform definition from specimen to specimen. Large cracks were present in the specimen gage section at the end of life, as shown in Fig. 4.

Plots of total, $\Delta\varepsilon_t$; plastic, $\Delta\varepsilon_p$; and elastic, $\Delta\varepsilon_e$, strain range versus cycles to failure (N_f) were constructed from the results of all-weld-metal fatigue tests for each of the temperatures under consideration. The Coffin-Manson-Basquin relationship

$$\Delta\varepsilon_t = \Delta\varepsilon_p + \Delta\varepsilon_e = AN_f^{-a} + BN_f^{-b} , \tag{1}$$

was generally obeyed, as shown in Figs. 5 and 6 for the 616 and 811 K tests, respectively. Similar plots at 295 and 866 K were omitted for brevity; however, values of the constants and coefficients for Eq. (1), as established by least squares analysis, are summarized in Table 2 for all temperatures investigated. Best fit total strain range lines showing the influence of temperature on the low-cycle strain-controlled fatigue life of ERNiCr-3 are plotted in Fig. 7.

Cyclic stress-strain curves were constructed from the hysteresis loops generated at various fractions of the cycle life; 1/4 cycle, cycle 10, and $N_f/2$. The data were fit by an equation of the form:

$$\Delta\varepsilon_t/2 = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2A}\right)^{1/n} , \tag{2}$$

where

$\Delta\sigma$ = stress range at indicated cycle,

E = Young's modulus taken as an average value from several hysteresis loops at a given temperature,

n, A = Cyclic strain hardening exponent and coefficient, respectively.

Examples comparing the 811 K cyclic stress-strain all-weld-metal data with the best fit curves are shown in Fig. 8. Cyclic hardening is apparent, with little or no differences evident in the cyclic stress-strain behavior of hot-or cold-wire weld metal. Further, no dependence of specimen orientation (longitudinal versus transverse) is apparent. Similar plots for the other temperatures investigated were constructed (omitted for brevity), and the values of the coefficients and exponents are given in Table 3.

Cyclic lives of strain-controlled composite hourglass-shaped weldment specimens are compared in Fig. 9 with best fit lines for annealed 2 1/4 Cr-1 Mo steel data [1] and the all-weld-metal data from Fig. 6. Lower strain-controlled fatigue life compared with the other materials is not surprising when one considers the variability in material properties and the presence of a metallurgical notch at the fusion line. The metallurgical notch was particularly important in the fatigue life of the specimens tested at strain ranges of 1 and 2% where in all cases cracks nucleated at the fusion line, as shown in Fig. 4. The cracks then propagated away from the fusion line into the 2 1/4 Cr-1 Mo steel ($\Delta\varepsilon_t$ = 2% tests), Fig. 4, or followed the fusion line ($\Delta\varepsilon_t$ 1% test). At the lower strain ranges, such as $\Delta\varepsilon_t$ = 0.45%, crack nucleation always occurred in the base metal at about 3 to 4 mm from the fusion line. The width of the HAZ in the composite specimens was also about 3 to 4 mm. Since the diametral extensometer was always situated such

SUMMARY REMARKS

When fatigue-induced failure of piping occurs, it is usually associated with cracking in the weld or HAZ material. The causes of failure have usually been attributed to poor weldment design, presence of defects, high residual stress levels, or metallurgical changes occurring within the HAZ. Successful design of weldments to be exposed to elevated temperature for prolonged periods of time is complicated because of the number of factors, including the dissimilarity of mechanical properties of base, HAZ, and weld metal. Residual stresses induced by thermal mechanical processing and metallurgical notches can cause high local discontinuity stresses. Further, weld-metal-like castings are known to display anisotropy in mechanical properties.

The information reported herein represents a partial fulfillment of the mechanical property needs as specified by the design community for the successful design of the CRBRP transition joints. Large differences in tensile properties were demonstrated between ERNiCr-3 weld metal and the HAZ and annealed 2 1/4 Cr-1 Mo steel. The low-cycle fatigue properties of as-deposited hot-and-cold-wire ERNiCr-3 weld metal were established. Although the continuous-cycle fatigue properties of as-deposited hot-wire weld metal were slightly superior to those of cold-wire-deposited weld metal, the cyclic stress-strain response differed little at 811 K. Further, neither the fatigue life nor the cyclic stress-strain response of the ERNiCr-3 weld metal depended upon the orientation of the specimen with respect to the fusion line (i.e., transverse versus longitudinal).

The results of tests conducted on the hourglass-shaped composite specimens, while limited, demonstrated that specimens could be fabricated and tested to provide information concerning the strain-controlled fatigue behavior of HAZ material. An exact knowledge of the axial cyclic strain within the HAZ is not possible because of the strength gradient across the HAZ as well as the stress discontinuity associated with material differences across the fusion line. Nonetheless, cyclic life and stress-strain response were reasonably reproducible, indicating that specimen fabrication methods and extensometer placement with respect to the fusion line could be duplicated. Accordingly, composite specimens of this design and others will be subjected to prolonged periods of thermal aging and subsequently subjected to continuous-cycle fatigue and creep-fatigue testing to determine if degradation of these properties occurs. Results of these tests will be reported in subsequent papers.

CONCLUSIONS

Several conclusions were drawn from this work:

1. The cyclic stress-strain and continuous cycle strain-controlled fatigue properties of as-deposited ERNiCr-3 were defined over the temperature range from 295 to 866 K. A comparison between ERNiCr-3 deposited by the automatic hot- and cold-wire gas tungsten-arc processes indicated that the fatigue life of hot-wire material was slightly superior. However, cyclic stress-strain response of the two materials was similar.

2. An hourglass-shaped fatigue specimen was employed to determine if HAZ fatigue and cyclic stress-strain response of a 2 1/4 Cr-1 Mo steel-ERNiCr-3 weldment could be determined. Resultant fatigue properties showed reasonable reproducibility, so this specimen geometry can be used for determining the influence of thermal aging on HAZ behavior.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided by the Energy Research and Development Administration. We also wish to recognize L. K. Egner and C. O. Stevens for their help in conducting many of the tests and to V. T. Houchin for his assistance in preparing the weld test plates.

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TABLE 1--Results From Strain-Controlled Fatigue Tests for All Weld Metal and HAZ Materials

Specimen	Weld Process[a] and Specimen Orientation[b]	Temperature, deg K	Total Strain Range,[c] $\Delta\varepsilon_t$ (%)	Range at 10th Cycle: Plastic Strain, $\Delta\varepsilon_p$ (%)	Range at 10th Cycle: Elastic Strain, $\Delta\varepsilon_e$ (%)	Range at 10th Cycle: Stress, $\Delta\sigma$ (MPa)	Range at $N_f/2$: Plastic Strain, $\Delta\varepsilon_p$ (%)	Range at $N_f/2$: Elastic Strain, $\Delta\varepsilon_e$ (%)	Range at $N_f/2$: Stress, $\Delta\sigma$ (MPa)	Modulus of Elasticity,[d] E (GPa)	Cycles To Failure,[e] N_f
8H511	H,T	295	2.99	2.29	0.70	987	2.35	0.64	1076	162	718
8H515	H,T	295	2.00	1.34	0.66	950	1.29	0.71	1090	158	1,[illegible]
8H501	H,T	295	0.96	0.53	0.43	811	0.44	0.52	901	171	3,547
8H514	H,T	295	0.70	0.27	0.43	780	0.19	0.51	933	182	12,152
8H219	H,T	295	0.57	0.27	0.30	696	0.16	0.42	811	205	13,831
8H205	H,T	616	2.99	2.33	0.66	809	2.17	0.82	1150	141	304
8H64A	H,L	616	1.95	1.40	0.55	793	1.26	0.69	1044	159	729
8H61A	H,L	616	1.46	0.95	0.51	694	0.80	0.66	936	143	877
8H211	H,T	616	0.96	0.58	0.38	603	0.38	0.58	931	166	2,944
8H63A	H,L	616	0.75	0.36	0.39	640	0.27	0.53	875	165	8,606
8H208	H,T	616	0.57	0.28	0.29	268	0.10	0.47	807	169	19,521
8W10	C,T	811	2.93	2.34	0.59	863	2.09	0.84	1212	166	154
8W23	C,T	811	2.00	1.44	0.56	843	1.30	0.70	1082	168	293
8W24	C,T	811	1.51	1.01	0.50	794	0.86	0.65	1039	172	520
8W22	C,T	811	1.49	1.00	0.49	737	0.86	0.[illegible]	961	150	38[illegible]
8W02	C,T	811	1.00	0.58	0.42	637	0.39	0.61	864	150	2,4[illegible]1
8W06	C,T	811	0.79	0.40	0.39	611	0.24	0.55	852	157	4,6[illegible]2
8W05	C,T	811	0.50	0.14	0.36	555	0.03	0.47	685	165	20,[illegible]93
8W09	C,T	811	0.45	0.10	0.35	523	0.02	0.43	623	146	191,566
8W04	C,T	811	0.40	0.09	0.32	516	0.03	0.37	539	144	88,878
8W03	C,T	811	0.35	0.01	0.34	443	0.01	0.34	517	148	2,571,449
8W502	H,T	811	2.50	2.01	0.49	779	[illegible].73	1.77	1141	162	299
8H507	H,T	811	2.00	1.48	0.52	723	1.27	0.73	1080	156	404
8H61A	H,L	811	1.68	1.68	0.4[illegible]	762	1.01	0.67	1013	151	511
8H509	H,T	811	1.50	0.98	0.52	684	0.75	0.75	988	130	1,176
8H513	H,T	811	0.83	0.41	0.42	629	0.21	0.62	849	160	4,727
8H506	H,T	811	0.82	0.33	0.49	475	0.17	0.66	811	131	11,070
8H62A	H,L	811	0.77	0.37	0.40	622	0.24	0.53	78[illegible]	155	5,159
8H508	H,T	811	0.57	0.17	0.40	560	0.05	0.52	722	140	15,530
8H201	H,T	811	0.45	0.14	0.31	461	0.06	0.39	599	153	65,229
8H512	H,T	811	0.41	...	...	...	0.03	0.38	557	149	150,798[f]
HC3	H,H	811	2.00	1.50	0.50	734	1.51	0.49	731	148	405
HC1	H,H	811	1.99	1.46	0.53	734	1.46	0.53	727	137	279
HC5	H,H	811	1.00	0.51	0.49	721	0.54	0.46	673	146	1,067
HC13	H,H	811	1.00	0.43	0.57	720	0.47	0.53	746	132	920
HC12	H,H	811	0.45	0.07	0.38	593	0.08	0.37	556	147	5,797
HC7	H,H	811	0.45	0.10	0.35	541	0.12	0.33	503	147	9,212
HC9	H,H	811	0.40	0.02	0.38	496	0.03	0.37	494	132	6,505
HC4	H,H	811	0.35	0.03	0.32	423	0.04	0.31	416	134	136,263[f]
8H209	H,T	866	2.90	2.33	0.57	699	2.11	0.79	984	133	125
8H206	H,T	866	1.96	1.45	0.51	713	1.25	0.71	1023	149	272
8H203	H,T	866	1.45	1.01	0.46	679	0.82	0.65	947	150	321
8H204	H,T	866	0.97	0.59	0.38	583	0.40	0.58	855	149	1,931
8H202	H,T	866	0.56	0.25	0.31	520	0.08	0.48	694	148	7,453
8H207	H,T	866	0.41[g]	0.09	0.32	457	0.01	0.34	485	141	442,600[f]

[a] C means automatic gas tungsten-arc process with cold wire filler additions; H hot wire.

[b] T means all-weld-metal uniform gage specimen with longitudinal axis transverse to the weld direction; L parallel; H hourglass specimen with 2 1/4 Cr-1 Mo steel heat affected zone (HAZ) located at specimen minimum diameter.

[c] Strain rate $4 \times 10^{-3} s^{-1}$.

[d] Measured from hysteresis loop

[e] Cycles to 20% decrease in stress range at $N_f/2$.

[f] Test discontinued with no cracks observed.

[g] Total strain range decreased early during the test to 0.35%.

TABLE 2--Values for the Elastic and Plastic Strain Range Constants for Tests Conducted at a Strain Rate of $4 \times 10^{-3} s^{-1}$

Weld Process[a]	Temperature, deg K	$\Delta\varepsilon_t = \Delta\varepsilon_p + \Delta\varepsilon_e = AN_f^{-a} + BN_f^{-b}$			
		A	a	B	b
H	295	727.28	0.887	1.71	0.139
H	616	104.23	0.687	1.51	0.116
C	811	55.34	0.662	1.15	0.087
H	811	84.72	0.695	1.52	0.110
H	866	48.08	0.671	1.30	0.112

[a] C Denotes automatic gas tungsten-arc welding process with cold-wire filler additions; H denotes automatic gas tungsten-arc welding process with hot wire additions.

TABLE 3--Cyclic Hardening Constants for Weld and Composite (HAZ) Material

Material	Temperature, deg K	Modulus of Elasticity, E (GPa)	$\Delta\varepsilon_t/2$[a] $= \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2A}\right)^{1/n}$					
			First Quarter Cycle		Tenth Cycle		Cycle $N_f/2$	
			A	n	A	n	A	n
Hot Wire	295	169	...	...	493	0.156	558	0.111
Hot and Cold Wire	616	160	...	...	417	0.211	557	0.113
Hot Wire	811	152	339	0.182	391	0.136	549	0.181
Cold Wire	866	149	244	0.066	352	0.143	520	0.126
Composite (HAZ)	811	141	393	0.223	407	0.115	412	0.154

[a]Cyclic stress-strain curves developed from strain-controlled fatigue tests at strain rate of $4 \times 10^{-3} s^{-1}$; $\Delta\varepsilon_t$ = total strain range, $\Delta\sigma$ = stress range.

LIST OF FIGURES

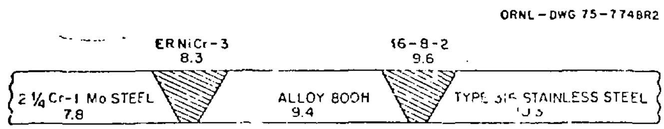

Fig. 1. Transition Joint Configuration. Mean coefficients of expansion from 295 to 811 K are noted below each material.

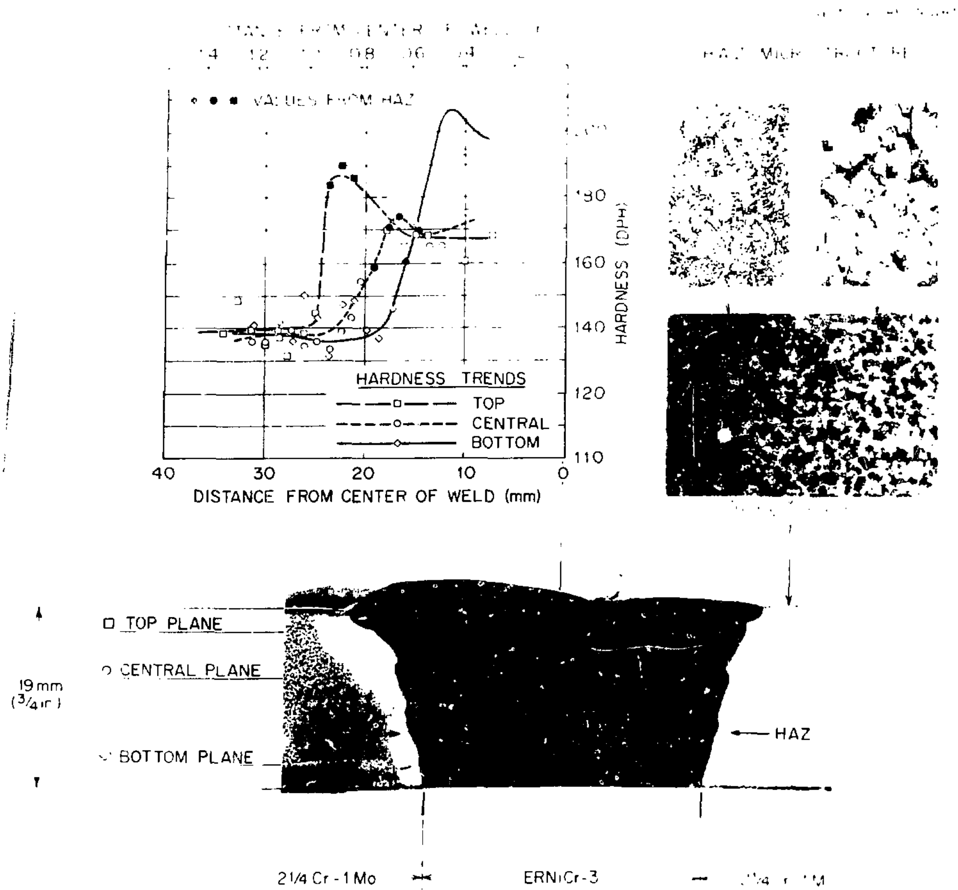

Fig. 2. Hardness Measurements on a Weld Joining 2 1/4 Cr-1 Mo Steel with ERNiCr-3 Filler Metal. The weldment was fabricated by the automatic gas tungsten-arc process with hot-wire filler additions and then stress relieved at 737°C (1005 K) for 1 hr.

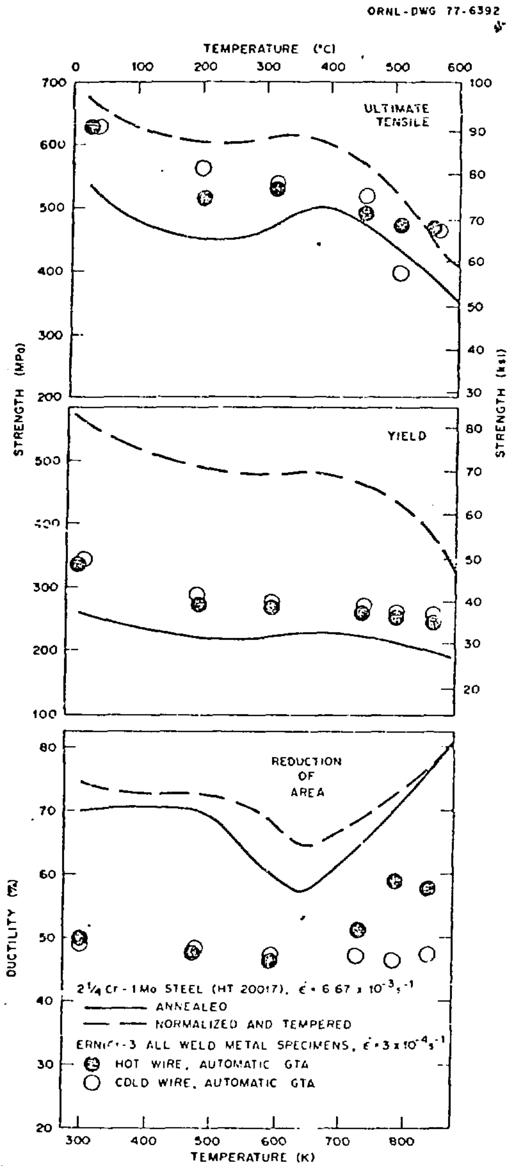

Fig. 3. Comparison of Tensile Properties of Base, HAZ, and ERNiCr-3 Weld Metal.

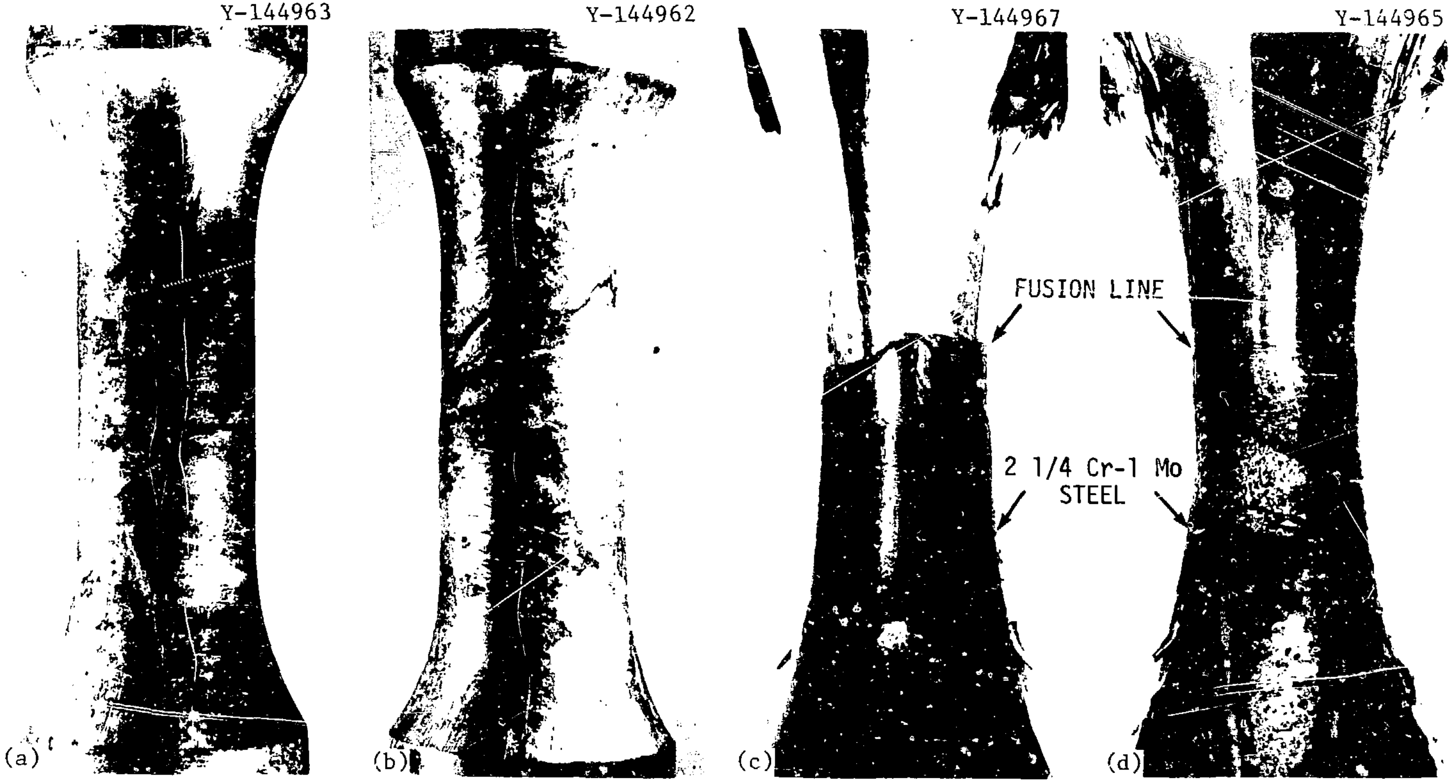

Fig. 4. Post-Fatigued Specimen Showing Cracks. 5×. (a) Specimen 8H508 all weld metal, $\Delta\varepsilon_t$ = 0.57%. (b) Specimen 8H507 all weld metal, $\Delta\varepsilon_t$ = 2.0%. (c) Specimen HC1 composite, $\Delta\varepsilon_t$ = 1.99%. (d) Specimen HC7 Composite, $\Delta\varepsilon_t$ = 0.45%.

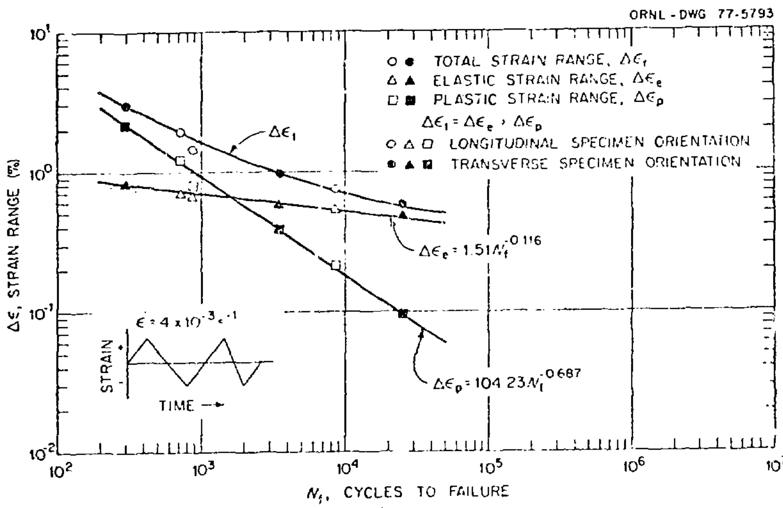

Fig. 5. Strain-Controlled Fatigue Behavior of ERNiCr-3 at 616 K. All-weld-metal specimens were prepared by gas tungsten-arc process with hot-wire filler additions.

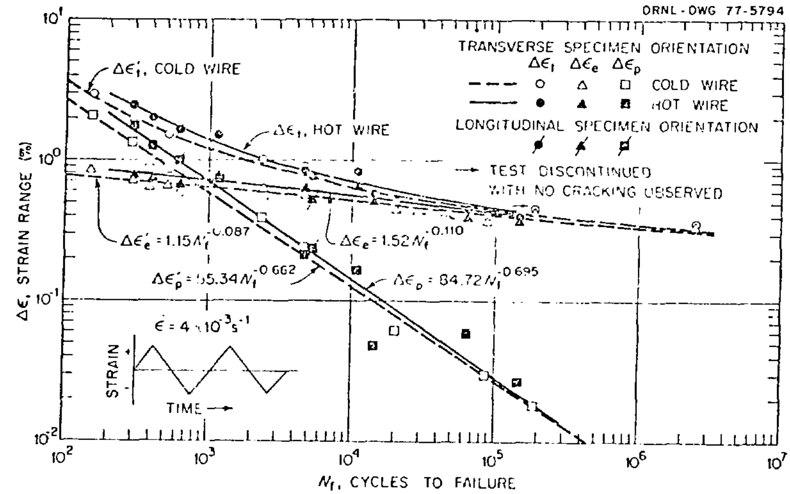

Fig. 6. Comparison of the Strain-Controlled Fatigue Behavior of ERNiCr-3 at 811 K. All-weld-metal specimens were prepared by automatic gas tungsten-arc processes with hot- and cold-wire filler additions.

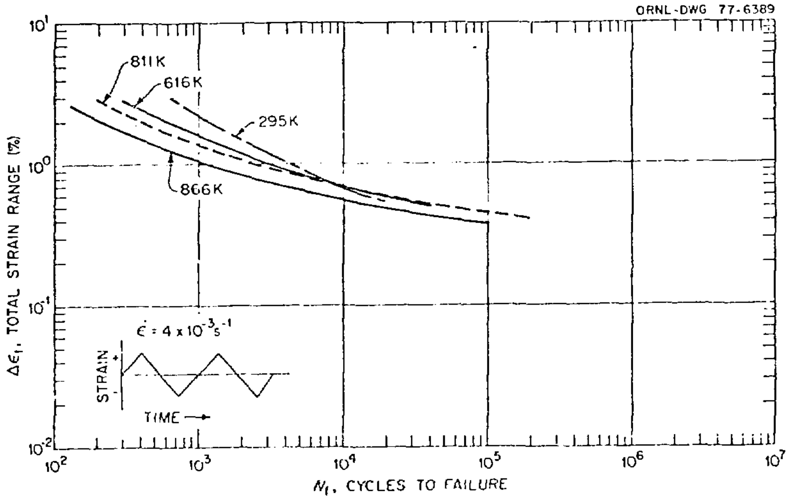

Fig. 7. Strain-Controlled Fatigue Behavior of ERNiCr-3 as a Function of Temperature. All-weld-metal specimens were prepared by automatic gas tungsten-arc process with hot-wire filler additions.

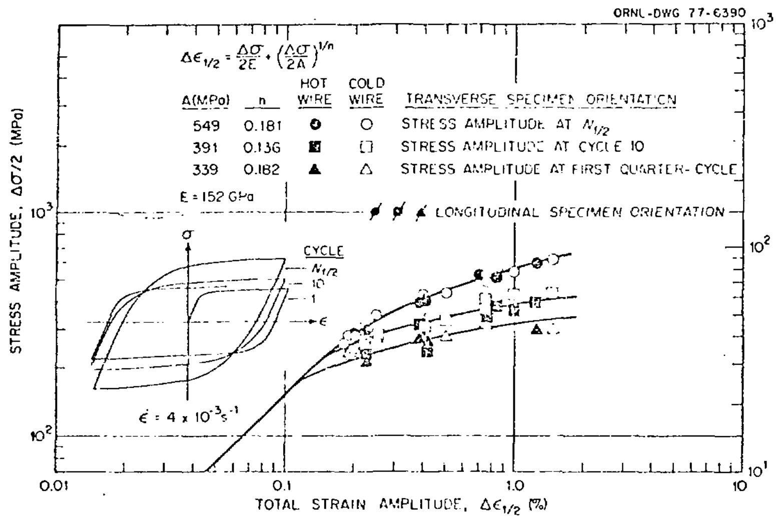

Fig. 8. Cyclic Stress-Strain Curves for ERNiCr-3 at 811 K.

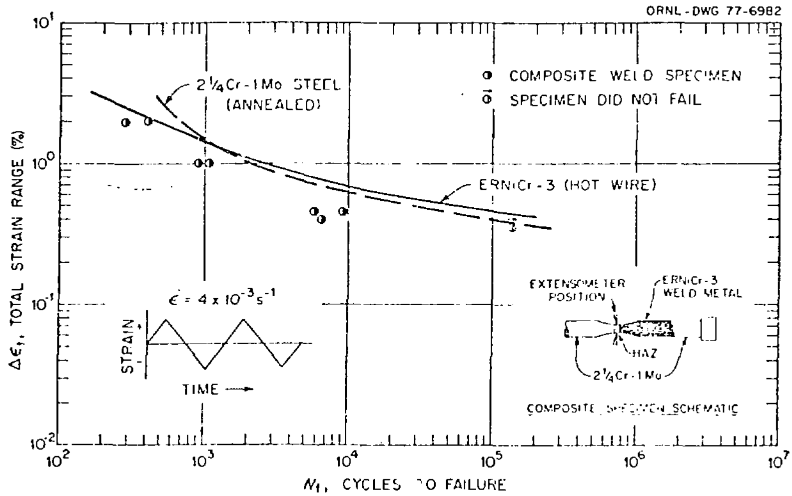

Fig. 9. Comparison of Fatigue Data From Composite Weld Specimens at 811 K and the Associated Component Materials: 2 1/4 Cr-1 Mo Steel and ERNiCr-3 Weld Metal.

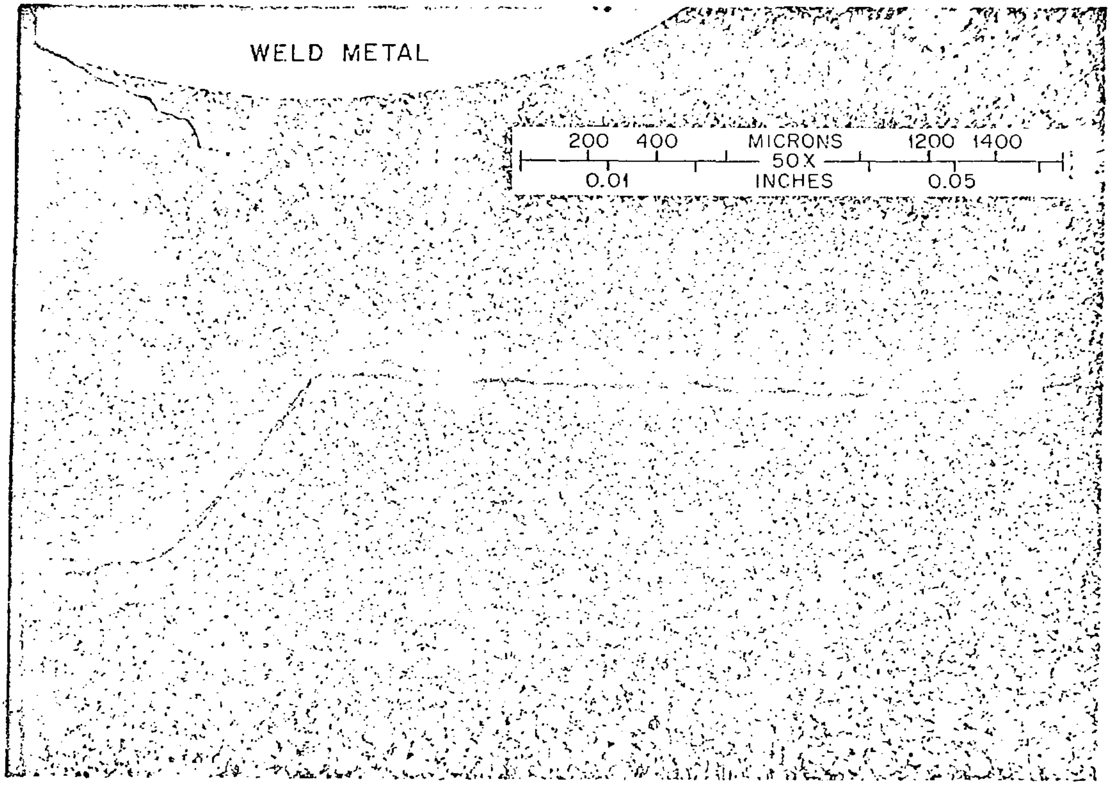

Fig. 10. Fatigue Cracking in HAZ.

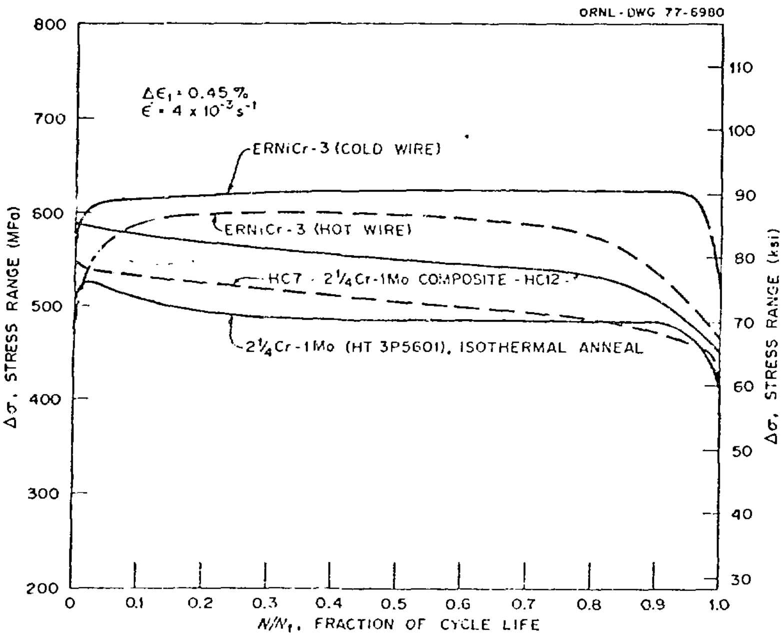

Fig. 11. Stress Range as a Function of Fraction of Cyclic Life for Several Transition Joint Materials at 811 K at a Total Strain Range of 0.45%.

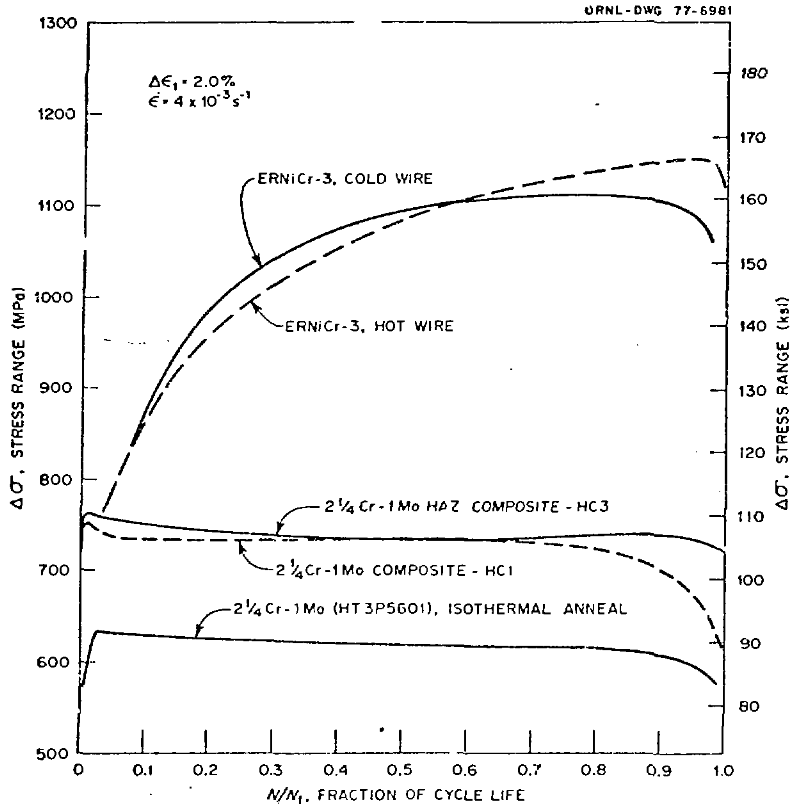

Fig. 12. Stress Range as a Function of Fraction of Cyclic Life For Several Transition Joint Materials at 811 K at a Total Strain Range of 2.0%.