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EVALUATION OF HASTELLOY X FOR GAS-COOLED-REACTOR APPLICATIONS

H. E. McCoy and J. F. King

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ABSTRACT

Hastelloy X is a potential structural material for use in gas-cooled reactor systems. In this application data are necessary on the mechanical properties of base metals and weldments under realistic service conditions. The test environment studied was helium that contained small amounts of H_2, CH_4, and CO. We found this environment to be carburizing with the kinetics of this process, becoming rapid above 800°C. Suitable weldments of Hastelloy X were prepared by several processes; those weldments generally had properties similar to the base metal except for lower fracture strains under some conditions. Some samples were aged up to 20,000 h in the test gas and tested, and some creep tests on as-received material exceeded 40,000 h. The predominant effect of aging was the significant reduction of the fracture strains at ambient temperature; the strains were lower when the samples were aged in HTGR helium than when aged in inert gas. Under some conditions aging also increased the yield and ultimate tensile strength. Limited impact testing showed that the impact energy at 25°C was reduced drastically by aging at 871 and 704°C. Creep tests failed to show effects of environment, aging, or welding on the creep strength of Hastelloy X; however, the fracture strain was lower for base metal in HTGR helium than in air and lower for weldments than for base metal.

1. INTRODUCTION

Although numerous alloys may be useful for specialized applications in gas-cooled systems, the alloy that would currently be selected as the predominant structural material is Hastelloy X,* a wrought nickel-base solid solution alloy of Ni, Cr, Fe, and Mo. Table 1 gives both the specified chemical limits of this alloy and the specific compositions of two heats of material evaluated in this study.

*Registered trademark of Cabot Corporation.

Table 1. Hastelloy X compositions

Element	Alloy (wt %)		
	Specified limits	Heat 4936	Heat 2792
Ni	Balance	Balance	Balance
Cr	20.5–23.0	21.82	21.25
Co	0.5–2.5	1.68	1.94
Mo	8.0–10.0	9.42	8.99
Fe	17.0–20.0	19.09	18.96
Si	1.0[a]	0.44	0.41
C	0.05–0.15	0.07	0.10
Mn	1.0[a]	0.58	0.57
S	0.03[a]	>0.005	>0.005
W	0.2–1.0	0.63	0.56
P	0.04[a]		
Other	0.01B[a]		

[a]Maximum.

Hastelloy X relies mainly on molybdenum as the solution strengthener, although it also contains cobalt and tungsten. The alloy composition allows intermetallic compounds to form and reduce the room-temperature impact energy following long-term aging. Despite this problem, Hastelloy X has been used extensively in parts for jet aircraft and in the petrochemical industry.

Several studies have been performed on Hastelloy X in gas-cooled reactor applications,[1–5] and many results of these studies are pertinent to our discussion.

1. From 538 to 871°C, Hastelloy X loses in ambient-temperature ductility, primarily from precipitation of cabides, but some sigma and mu phases are formed at the high temperatures.
2. Internal oxidation is shallow at 900°C and below, reaching 10 to 20 μm in 10,000 h.
3. Carburization becomes rapid at 900°C and above so that carburization to a depth of about 10 mm would be predicted for 100,000 h.

4. Creep strength is not affected by carburization under the conditions studied.
5. Test results disagree considerably as to whether or not carburization degrades the fracture strain below that caused by thermal aging. Studies at the same laboratory showed considerable heat-to-heat variation.

The purpose of our study was to extend the data base for Hastelloy X, with particular emphasis on ductility degradation during creep and aging studies. Tests were conducted on base metal and weldments for aging times up to 20,000 h and creep test times up to 30,000 h.

2. EXPERIMENTAL DETAILS

2.1 MATERIALS

The several test materials involved in this program and their chemical compositions and product forms are presented in Table 2. Heats 4936 and 2792 of Hastelloy X base metal were studied. The three welds evaluated and the material combinations are summarized in Table 3. Two welding processes involving the same heat 4345 of Hastelloy X weld wire were evaluated. In welding by the gas tungsten arc (GTA) process, the weld wire was used bare; the same heat of weld wire was coated for use in making welds by the shielded metal arc (SMA) welding process.

2.2 TEST SPECIMENS

The geometry of the test specimen is shown in Fig. 1. A good feature of the specimen is the absence of threads. The grips align on the 6.35-mm (0.250-in.) diameter and pull against the surface, inclined at 60°. The extensometer attaches by set screws to the two grooves, which have an included angle of 100°.

Base metal specimens were oriented so that the specimen axis was parallel with the primary working direction. Transverse weldment specimens were taken so that the gage section of the specimen spanned the weld

Table 2. Characterization of Hastelloy test materials

(All material except wire solution annealed by vendor, Cabot Corporation)

Element	Chemical analysis (%)				
	Heat 4936[a,b]	Heat 2792[b,c]	Heat 4284[b,d]	Heat 4345[b,c]	Heat 7180[f,g]
Ni	Bal	Bal	Bal	Bal	Bal
Cr	21.82	21.25	21.79	21.92	15.15
Co	1.68	1.94	2.40	2.09	0.06
Mo	9.42	8.99	8.82	8.85	14.46
Fe	19.09	18.96	19.06	18.81	0.44
Al	0	0	0	0	0.25
Si	0.44	0.41	0.35	0.40	0.38
C	0.07	0.10	0.06	0.08	0.006
Mn	0.58	0.57	0.59	0.70	0.47
S	<0.005	<0.005	<0.005	<0.005	0.006
W	0.63	0.56	0.63	0.42	<0.10
La					0.019

[a]Plate, 12.7 mm (1/2 in.).

[b]Hastelloy X.

[c]Bar, 31.8 mm (1 1/4 in.).

[d]Plate, 12.7 mm (1/2 in.).

[e]Wire, 8 mm (5/16 in.).

[f]Wire, 2 mm (1/16 in.).

[g]Hastelloy S filler.

Table 3. Summary of weldment designations and wrought material heats

Weld designation[a]	Base metal[b]	Weld metal[b]	Weld process[c]
X/X/X, GTA	4284	4345	GTA
X/X/X, SMA	4284	4345	SMA
X/S/X, GTA	4284	7180	GTA

[a]Designation denotes base metal/filler metal/base metal in terms of Hastelloy designation.

[b]See Table 2 for description of each heat.

[c]GTA, gas tungsten arc; SMA, shielded metal arc.

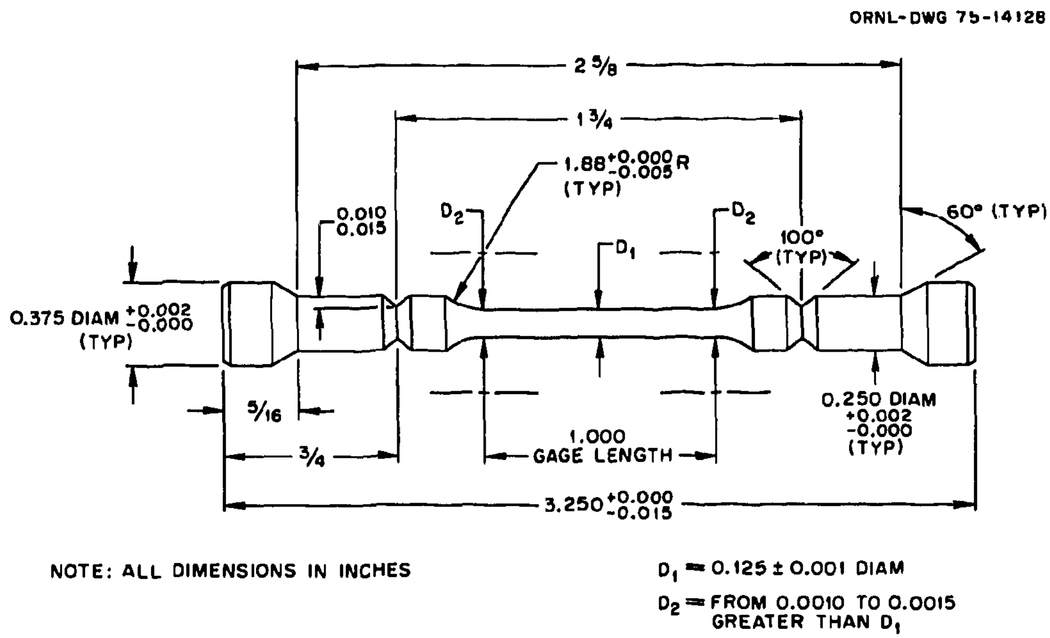

Fig. 1. Details of creep specimens for environmental tests. To convert dimensions to millimeters, multiply by 25.4.

and contained the base metal, the weld metal, and the heat-affected zone. All-weld metal specimens were cut so that they were parallel to the weld, and the gage section consisted totally of weld metal.

2.3 TESTING EQUIPMENT

The creep testing chambers used in this study were described in detail previously,[5] and a typical test stand is shown in Fig. 2. Most test retorts are made of 51-mm (2-in.) schedule 40 type 304L stainless steel pipe, but a few retorts, operated at 871°C, are made of aluminum oxide. The seal between the pull rods and the environment is made with neoprene U-cups, which are also used to seal the four extensometer rods that exit from the bottom of the test chamber.

Some samples aged in inert environments at 538, 704, and 871°C were simply stacked in metal containers, which were later evacuated, filled with an inert gas, and welded shut. Specimens were aged approximately 20,000 h in HTGR helium in the stainless steel retorts shown in Fig. 3. Aging is continuing in these retorts at 593 and 704°C, but the retort operating at 871°C was replaced with aluminum oxide and the specimens simply stacked in place.

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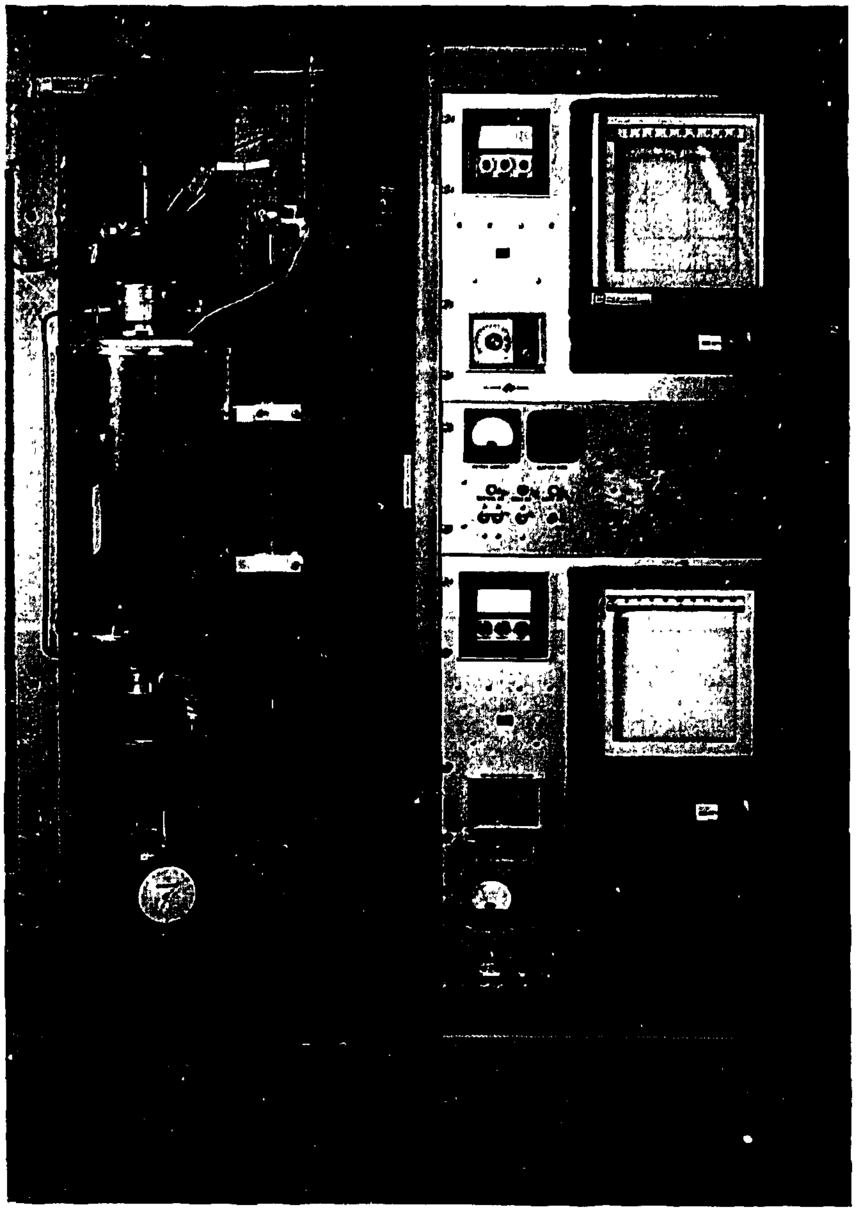

Fig. 2. Typical environmental creep test unit. Top half of the instrumentation rack contains control instruments for this machine, and bottom half services machine to right (not shown).

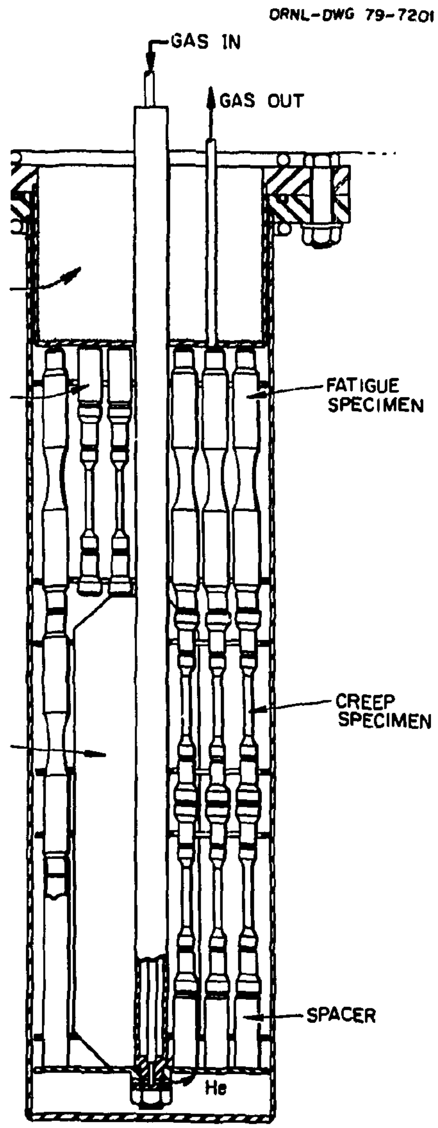

Fig. 3. Environmental exposure chamber.

2.4 TEST ENVIRONMENT

The test gas, premixed by the Matheson Company, Inc., and received in pressurized cylinders, is fed into a manifold maintained at 83 kPa, gage (12 psig). The piping and valves are arranged so that parallel streams of gas can be passed through each test retort and either returned to a sample manifold or vented. The gas stream can be passed through a gas chromatograph and the moisture monitored either before or after it passes through the test retort. The gas flow to each retort is maintained at 15 to 100 cm^3/min, with the criteria being to use a high enough flow rate to keep the gas stream from being detectably depleted in reactants. The helium composition in the test chamber is [in pascals (microatmospheres)] 34.0 (337) H_2, 3.2 (32) CH_4, 1.9 (19) CO, 0.2 (2) H_2O, and <0.05 (<0.5) N_2. Oxygen is removed by reaction with the H_2 as the gas passes through a furnace at 500°C.

The on-line analytical system consists of a 2110 Bendix gas chromatograph and a model 2100 Panametrics moisture analyzer. The chromatograph is calibrated by use of a certified standard prepared by the Matheson Company, Inc., and weekly readings are made routinely on each machine. Manufacturer's calibrations for the moisture monitors were used without verification. On several occasions monitors were placed in series and agreed within a factor of 2. Equilibrating the moisture probes (and the remainder of the system) to read low moisture values is so difficult that about 24 h is required to obtain reliable values.

The standard test start up consisted of assembling the new test specimen in the chamber; evacuating air from the chamber; pressurizing the chamber with test gas and establishing flow at 83 kPa, gage (12 psig); leak checking with a helium sniffer; heating to 400°C and holding for at least 24 h until moisture was less than 10 ppm; heating to test temperature; and applying load to start the test. We found that all impurities were initially high but that the outgassing period at 400°C allowed the gas composition to reach the desired operating level. Some elevation in impurity levels (less than a factor of 2) occurred during heating to the test temperature, but the gas reached the desired operating levels within 24 h.

3. RESULTS OF TENSILE TESTS

3.1 BASE METAL

Tensile test results for Hastelloy X (heat 4936) aged under a variety of conditions are given in Table 4. The maximum aging time was 20,000 h, and the aging environments were flowing HTGR helium and static inert gas. Tests following aging generally involved a tensile test at about 25°C and

Table 4. Tensile properties of as-received and aged Hastelloy X base metal (heat 2600-3-4936)

Test	Aging conditions				Test temperature		0.2% Yield strength		Ultimate tensile strength		Elongation (%)		Reduction of area %	Type specimen[b]
	Temperature		Time (h)	Environment[a]	(°C)	(°F)	(MPa)	(ksi)	(MPa)	(ksi)	Uniform	Total		
	(°C)	(°F)												
14892			0		22	72	359	52.0	762	110.5	43.8	50.5	59.8	A
14893			0		22	72	349	50.6	764	110.8	43.9	51.5	59.2	A
14894			0		22	72	350	50.8	764	110.8	44.3	51.9	61.4	A
17885	538	1,000	2,500	I	22	72	333	48.3	764	110.8	49.5	55.5	54.4	A
17886	538	1,000	2,500	I	22	72	340	49.3	766	111.2	46.8	54.4	50.0	A
17889[c]	704	1,300	2,500	I	22	72	482	69.9	916	132.9	7.7	7.7	8.7	A
17890[c]	704	1,300	2,500	I	22	72	476	69.0	939	136.1	9.8	9.8	8.1	A
17893	871	1,600	2,500	I	22	72	367	53.3	835	121.1	15.8	15.8	14.7	A
17894	871	1,600	2,500	I	22	72	368	53.4	818	118.7	13.4	13.4	12.3	A
XC7	538	1,000	10,000	I	22	72	385	55.9	777	112.7	43.1	43.2	39.7	A
XC25	704	1,300	10,000	I	22	72	357	51.8	854	123.8	18.2	18.2	16.1	A
XC43	871	1,600	10,000	I	22	72	399	57.9	732	106.2	15.0	15.1	10.5	A
X-100	593	1,100	10,000	H	24	75	385	55.9	770	111.7	40.2	43.4	49.5	B
X-104	704	1,300	10,000	H	24	75	578	83.8	1,054	152.9	10.8	10.8	14.0	B
X-108	871	1,600	10,000	H	24	75	401	58.1	846	122.7	10.0	10.0	9.3	B
XC14	538	1,000	20,000	I	24	75	355	51.5	787	114.1	44.8	46.8	36.9	B
XC32	704	1,300	20,000	I	24	75	350	50.7	832	120.7	9.5	9.5	8.1	B
XC50	871	1,600	20,000	I	24	75	325	47.2	791	114.7	18.0	18.0	14.5	B
X113	593	1,100	20,000	H	24	75	398	57.7	807	117.1	23.2	23.7	29.7	B
X117	704	1,300	20,000	H	24	75	540	78.3	1,098	159.3	8.2	8.2	3.5	B
X121	871	1,600	20,000	H	24	75	325	47.2	779	113.0	10.6	10.6	13.7	B
14807			0		538	1,000	239	34.6	592	85.8	46.5	49.9	40.9	A
14808			0		538	1,000	221	32.1	596	86.5	43.9	48.8	31.4	A
17887[d]	538	1,000	2,500	I	538	1,000	222	32.2	603	87.5	54.0	58.6	48.0	A
17888[c,d]	538	1,000	2,500	I	538	1,000	227	32.9	601	87.2	49.3	52.7	35.5	A
XC8[d]	538	1,000	10,000	I	538	1,000	236	34.2	600	87.0	48.6	48.7	42.9	A
XC15	538	1,000	20,000	I	538	1,000	226	32.8	580	84.1	46.8	47.7	41.7	A
X-101	593	1,100	10,000	H	593	1,100	176	25.5	521	75.6	62.3	65.2	44.4	B
X-112	593	1,100	20,000	H	593	1,100	292	42.3	664	96.3	20.9	21.4	21.1	B

Table 4. (Continued)

Test	Aging conditions				Test temperature		0.2% Yield strength		Ultimate tensile strength		Elongation (%)		Reduction of area %	Type specimen[b]
	Temperature		Time (h)	Environment[a]	(°C)	(°F)	(MPa)	(ksi)	(MPa)	(ksi)	Uniform	Total		
	(°C)	(°F)												
14799			0		704	1,300	223	32.4	425	61.6	23.0	48.5	41.7	A
14800			0		704	1,300	215	31.2	452	65.5	29.9	37.3	33.6	A
14801			0		704	1,300	212	30.8	460	66.7	30.8	37.3	35.9	A
17891	704	1,300	2,500	I	704	1,300	294	42.6	443	64.3	6.3	58.1	55.0	A
17892	704	1,300	2,500	I	704	1,310	284	41.2	429	62.2	5.9	74.2	58.2	A
XC26	704	1,300	10,000	I	704	1,300	230	33.3	439	63.7	11.1	36.3	37.5	A
X-105	704	1,300	10,000	H	704	1,300	359	52.1	588	85.3	8.6	21.6	29.0	B
XC33	704	1,300	20,000	I	704	1,300	249	36.1	420	60.9	10.4	47.3	49.1	A
X-116	704	1,300	20,000	H	704	1,300	368	53.4	590	85.6	3.7	25.3	28.1	B
14815			0		871	1,600	161	23.4	165	24.0	2.1	79.8	88.9	A
14898			0		871	1,600	163	23.6	168	24.3	2.3	84.4	88.2	A
17895	871	1,600	2,500	I	871	1,600	146	21.2	161	23.4	2.5	96.4	82.4	A
17896	871	1,600	2,500	I	871	1,600	141	20.4	159	23.0	2.5	101.0	86.3	A
XC43	871	1,600	10,000	I	871	1,600	151	21.9	162	23.5	5.8	78.5	94.5	A
X-109	871	1,600	10,000	H	871	1,600	211	30.6	239	34.7	5.0	59.4	68.9	B
XC51	871	1,600	20,000	I	871	1,600	188	27.3	232	33.7	6.4	74.4	70.2	A
X-120	871	1,600	20,000	H	871	1,600	191	27.7	249	36.1	1.8	46.0	47.8	B

[a] I, inert; H, HTGR helium.

[b] A, 6.4 mm (0.25 in.) in diameter × 3.18 cm (1.25 in.) long; B, 3.2 mm (0.125 in.) in diameter × 2.54 cm (1.00 in.) long.

[c] Broke at gage mark.

[d] Serration occurred before 0.2% yield.

one test at the aging temperature. If the samples were aged in HTGR helium, reaction with the test gas resulted in carburization and formation of a surface oxide on the Hastelloy X. The reaction rate was so high in the aging chamber operating at 871°C that it was not possible to maintain sufficient gas flow to avoid alteration of the gas composition. When the first samples were removed after 10,000 h, the test chamber was changed to an alumina tube. It was then possible to maintain the inlet and outlet gas streams at the same compositions. The average carbon concentrations of the aged samples are given in Table 5.

Table 5. Typical average carbon concentrations of aged samples

Aging conditions		Carbon concentration[a] (%)
Temperature (°C)	Time (h)	
593	10,000	0.084, 0.084
704	10,000	0.093, 0.093
871	10,000	0.083, 0.083
593	20,000	
704	20,000	0.096, 0.097
871	20,000	

[a]Carbon concentration of starting material was 0.07%.

Assessment of the property changes directly from the voluminous data in Table 4 is quite difficult; several groups of data will therefore be presented to make specific points. The yield and ultimate tensile strengths of samples aged at elevated temperatures and tested at 25°C are compared with those of the unaged material in Fig. 4. Aging at 704°C had the greatest effect on strength. The samples aged in an inert environment showed increases of about 25% in both yield and ultimate stength after aging for 2500 h but decreased in the degree of strengthening with further aging. In contrast, the samples aged in HTGR helium continued to increase in strength after longer aging times. This indicates that the carburization occurring in the HTGR helium leads to the formation of carbides

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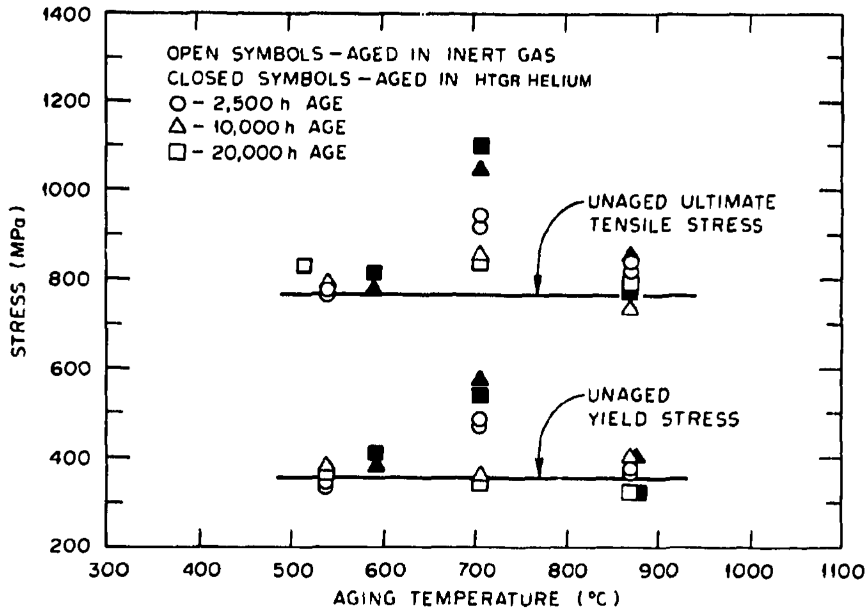

Fig. 4. Influence of aging on yield and ultimate tensile stresses of Hastelloy X base metal (heat 4936) at 25°C.

having morphologies that are strengthening. The strength variations in samples exposed to the inert and helium environments at higher and lower temperatures are very small.

The reduction of area of the same samples is shown in Fig. 5. The changes from aging in inert gas or helium at 538 and 593°C are quite small, with the lowest value being about 30% after aging 20,000 h at 593°C in helium. Aging at 704°C caused large decreases in the reduction of area. Lower values were obtained after the longest aging times and after aging in helium, compared with inert gas. The lowest value obtained was 3.5% after aging 20,000 h at 704°C in helium. The same general trends occurred after aging at 871°C, but the property changes after 20,000 h of aging were less than those observed after aging at 704°C. The smallest value was 9.3% after aging for 10,000 h at 871°C in helium.

The total elongations at fracture for these samples are shown in Fig. 6. The trend of decreasing elongation with aging is obvious, particularly at 704 and 871°C. After aging at 704 or 871°C for a few

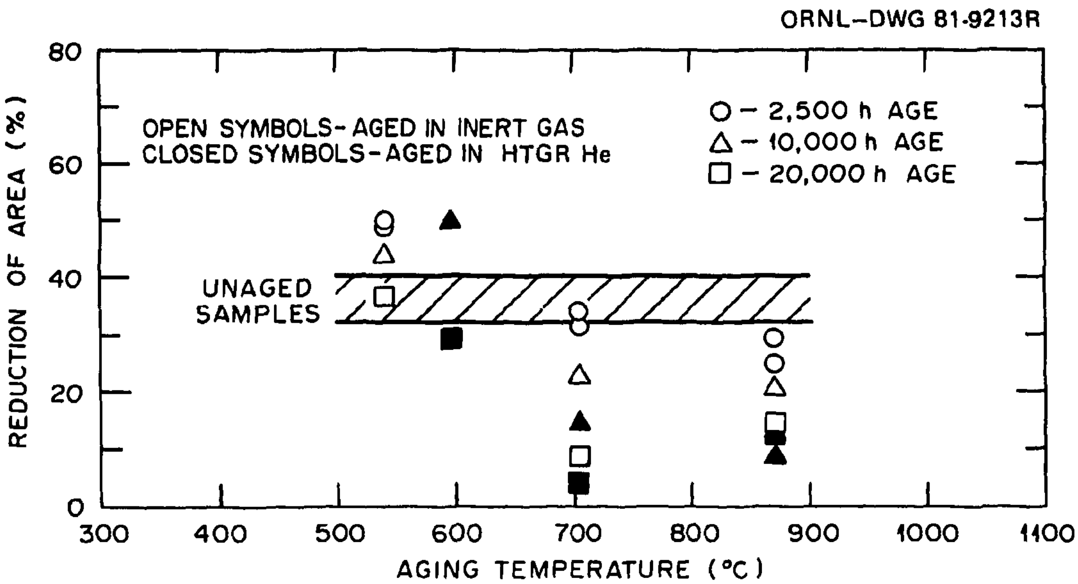

Fig. 5. Influence of aging on reduction of area of Hastelloy X (heat 4936) tested at 25°C.

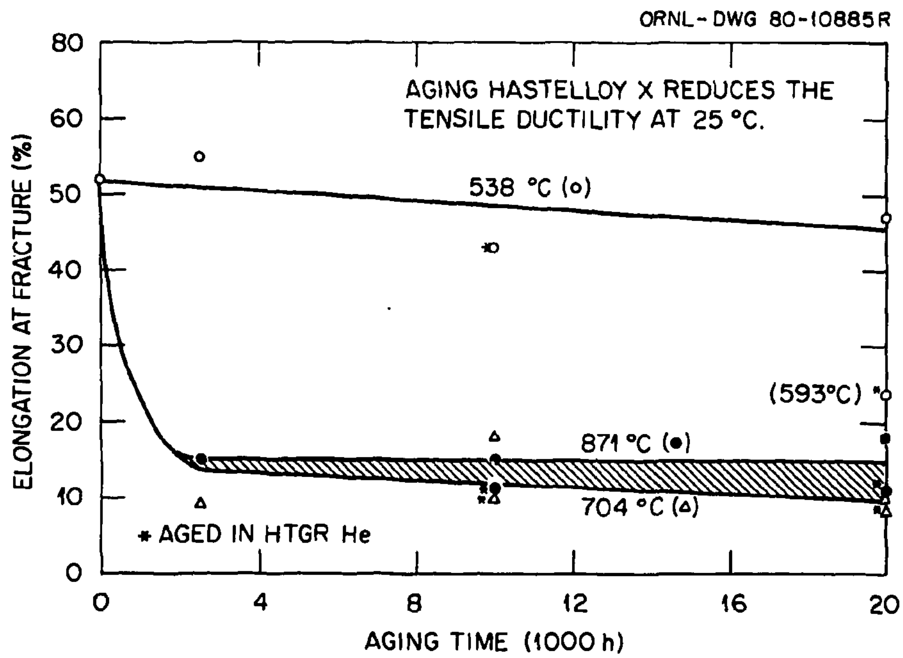

Fig. 6. Aging Hastelloy X (heat 4936) reduces the tensile ductility at 25°C.

thousand hours, the elongation was reduced to values of 10 to 20%; the lowest value obtained was 8.2% after aging 20,000 h at 704°C in helium. In all cases the elongation after aging in helium was less than that obtained after aging in inert gas.

Several of the aged samples were tensile tested at the aging temperature. Detailed test results are given in Table 4, and selected parameters are shown graphically in Figs. 7 and 8. The yield and ultimate tensile strengths are shown in Fig. 7 both for samples in the as-received condition and for those aged for 20,000 h in inert gas or in HTGR helium. These tests indicate that the as-received samples and the samples aged for 20,000 h in inert gas had identical strength properties. However, the samples aged for 20,000 h in helium had strengths above those of the as-received samples, with the largest increase at 704°C. The elongations of these samples at fracture are shown in Fig. 8. The values are equivalent for the as-received samples and the samples aged for 20,000 h in inert gas. However, the samples aged in HTGR helium had significantly lower fracture elongations, with the lowest value of 21.4% occurring after aging for 20,000 h at 593°C.

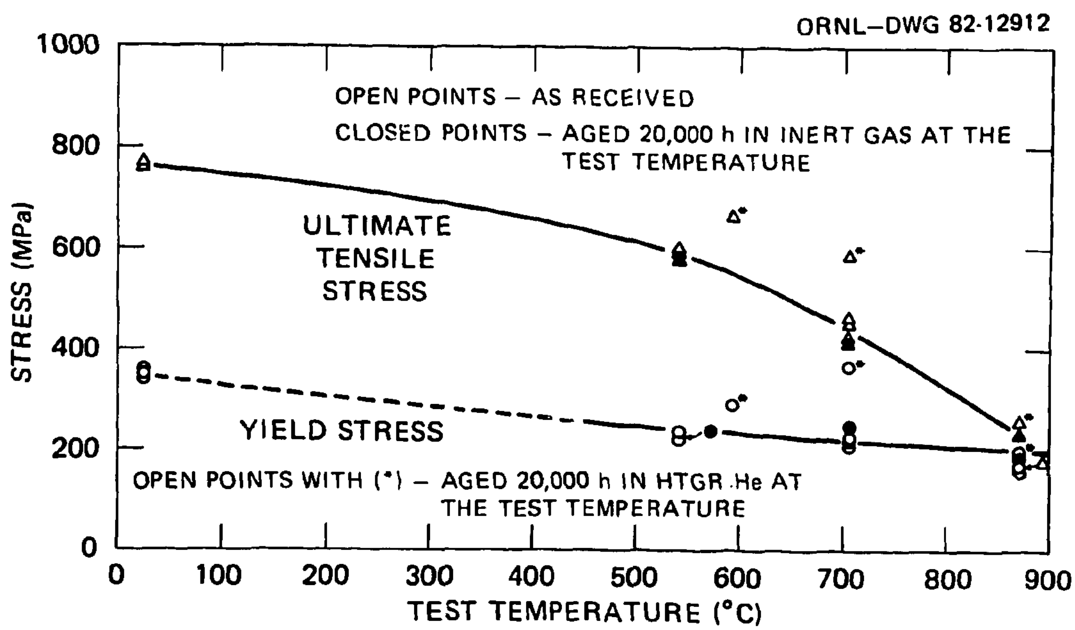

Fig. 7. Influence of aging on yield and tensile strengths of Hastelloy X (heat 4936) aged and tested at the same temperature.

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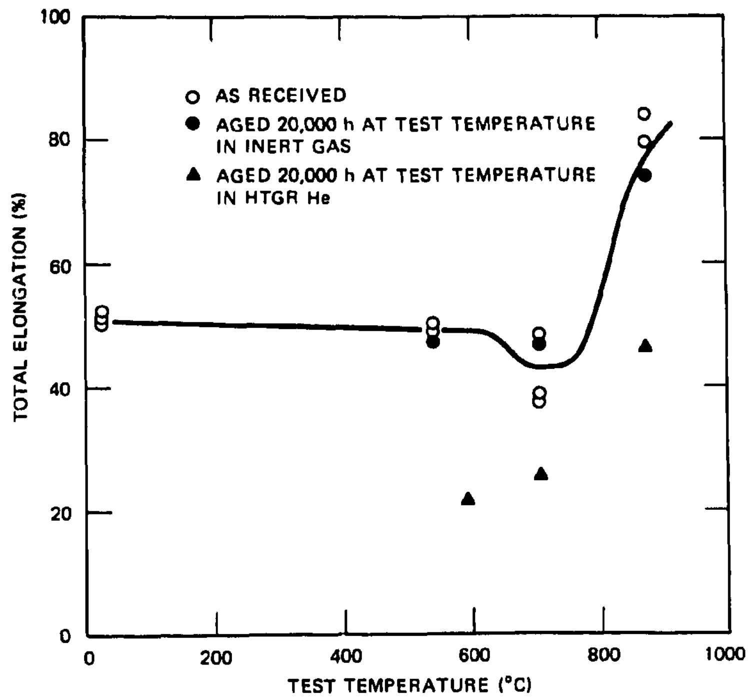

Fig. 8. Influence of aging on elongation of Hastelloy X (heat 4936) aged and tested at the same temperature.

3.2 WELD SAMPLES

Three types of weldments involving Hastelloy X base metal (heat 4284) were evaluated. The material and welding process combinations are summarized in Table 3. In one type of weldment using Hastelloy X filler material and the GTA process, two types of samples were taken. Samples were taken along the longitudinal axis of the weld so that they consisted entirely of weld metal; results of these tests are given in Table 6. The yield and tensile strengths of these samples are compared with those of Hastelloy X (heat 4936) base metal in Fig. 9; the weld metal is stronger over the entire test temperature range. The elongation and reduction of area values for these test samples are compared in Fig. 10. The elongation values at fracture are consistently lower for the weld metal than for the base metal over the entire range of test temperatures. The largest difference occurred at the highest temperature, at which the weld metal sample had only about one-half the elongation of the base metal

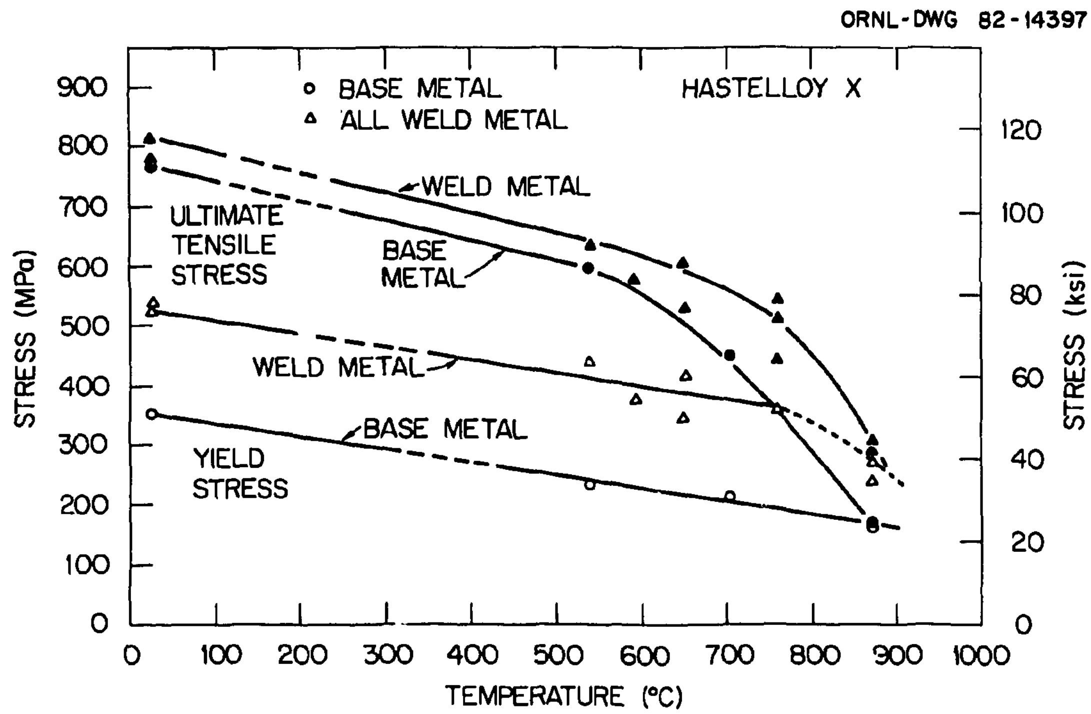

Fig. 9. Comparison of tensile strength parameters of Hastelloy X base (heat 4936) and weld (heat 4345) metal samples.

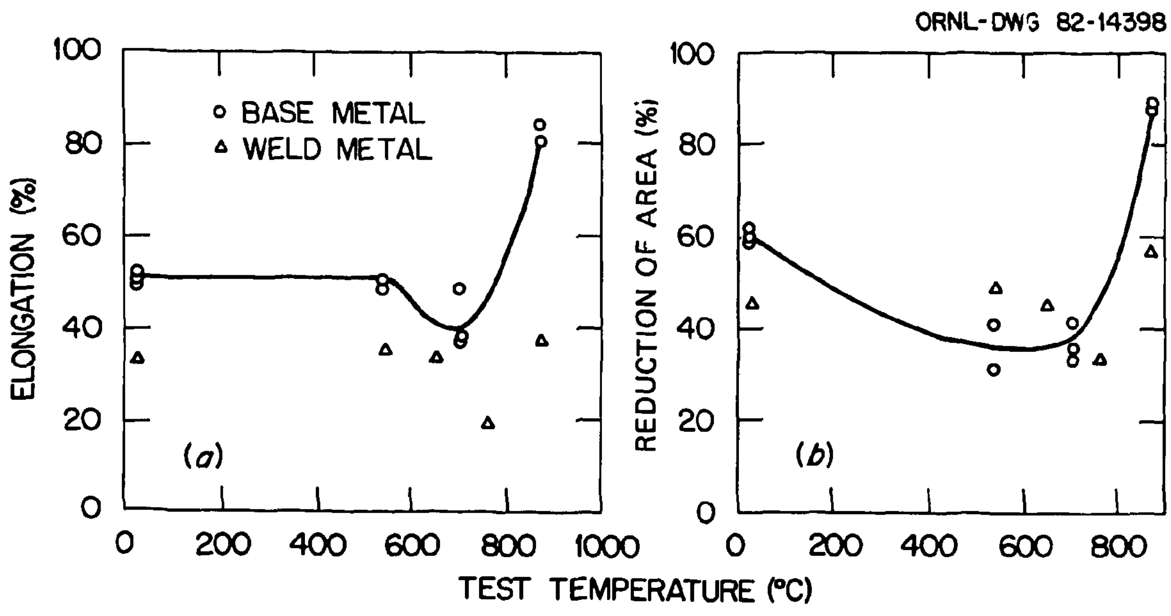

Fig. 10. Comparison of ductility parameters of Hastelloy X base (heat 4936) and weld (heat 4345) metal samples.

Table 6. Tensile properties of Hastelloy X welded with Hastelloy X by the gas tungsten arc (GTA) process

Test[a]	Weld	Test temperature		0.2% Yield strength		Ultimate tensile strength		Elongation (%)		Reduction of area (%)
		(°C)	(°F)	(MPa)	(ksi)	(MPa)	(ksi)	Uniform	Total	
16832	All weld[b]	25	77	528	76.6	811	117.6	30.5	33.7	45.7
16833	All weld[b]	538	1000	440	63.8	634	91.9	33.0	35.7	48.9
16834	All weld[b]	649	1200	416	60.4	603	87.4	31.4	33.7	44.9
16835	All weld[b]	760	1400	437	63.4	541	78.5	4.2	19.5	33.3
16836	All weld[b]	871	1600	291	42.2	302	43.8	5.0	37.3	56.7

[a]Tensile properties of Hastelloy X weld metal.

[b]All weld, GTA weld deposit of heat 4345.

sample at failure. The reduction of area values (Fig. 10) exhibit the same trends as does the elongation at high and low temperatures. However, from 500 to 800°C very little difference is apparent in the reduction of area values for the base and weld metal samples, and the reduction of area is slightly lower for the base metal at several temperatures.

Transverse samples were taken from all three types of weldments so that they included base metal, heat-affected zone, and weld metal. They were tested in the as-welded condition and after aging 2000 and 10,000 h in inert gas. Samples of the GTA Hastelloy X weldment were also aged 10,000 and 20,000 h in HTGR helium. The results of tensile tests on these samples are summarized in Tables 7, 8, and 9, and selected properties will be shown graphically.

The yield and ultimate tensile stresses of the three weldments in the as-welded condition are compared with those of the base metal in Fig. 11. All three weldments had similar strengths; yield strengths of the weldments were greater than those of the base metal over the entire range of test temperatures. The ultimate tensile strengths of the weldments were similar to those of the base metal at 25°C and became progressively stronger than those of the base metal as the test temperature was increased. The elongation and reduction of area values are compared in Fig. 12 for the three weldments and the base metal. The base metal had greater elongation at failure than did the weldments over the entire range

Table 7. Tensile properties of Hastelloy X welded with Hastelloy X filler metal by the gas tungsten arc (GTA) process

Test	Aging conditions: Temperature (°C)	Aging conditions: Temperature (F°)	Aging conditions: Time (h)	Aging conditions: Environment	Test temperature (°C)	Test temperature (°F)	0.2% Yield stress (MPa)	0.2% Yield stress (ksi)	Ultimate tensile stress (MPa)	Ultimate tensile stress (ksi)	Elongation (%) Uniform	Elongation (%) Total	Reduction in area (%)	Location of fracture	Weld reduction in area (%)
16703					25	77	456	66.2	725	105.2	38.0	40.0	44.1	W[a]	44.1
16704					593	1,100	304	44.1	548	79.5	33.0	33.5	52.2	W	44.1
16705	*b*	*b*			659	1,200	308	44.6	535	77.6	36.0	36.8	43.8	W	43.8
16706					760	1,400	283	41.0	443	64.2	15.0	30.9	36.4	B[c]	33.0
16707					871	1,600	248	35.9	262	38.0	5.0	26.0	79.7	W	79.7
16776	593	1,100	2,000	I	25	77	492	71.3	855	124.0		28.8	35.[illegible]	B	30.8
16778	649	1,200	2,000	I	25	77	720	104.4	1,112	161.3		5.1	1[illegible].5	W	13.5
16780	760	1,400	2,000	I	25	77	557	80.8	996	144.4		8.6	11.1	W	11.1
16782	871	1,600	2,000	I	25	77	376	54.6	784	113.7		12.8	22.8	W	22.8
16777	593	1,100	2,000	I	593	1,100	334	48.4	628	91.1		25.2	44.7	B	23.3
16779	649	1,200	2,000	I	649	1,200	524	76.0	695	100.8		9.8	30.5	W	30.5
16781	760	1,400	2,000	I	760	1,400	351	50.9	437	63.4	9.0	21.3	56.2	W	56.2
16783	871	1,600	2,000	I	871	1,600	198	28.7	244	35.4	7.0	49.8	75.4	W	75.4
122-9	593	1,100	10,000	I	25	77	511	74.1	820	118.9	17.8	18.5	37.5	B	3.4
122-13	649	1,200	10,000	I	25	77	590	85.6	1,113	161.4	6.1	6.1	10.3	W	10.3
122-17	760	1,400	10,000	I	25	77	480	69.6	859	124.6	6.5	6.5	9.2	W	9.2
122-21	871	1,600	10,000	I	25	77	348	50.4	700	101.6	10.6	10.6	16.5	W	16.5
122-10	593	1,100	10,000	I	593	1,100	359	52.0	666	96.6	19.6	20.4	39.8	B	5.1
122-14	649	1,200	10,000	I	649	1,200	516	74.8	704	102.1	6.4	12.7	36.7	W	36.7
122-18	760	1,400	10,000	I	760	1,400	330	47.8	450	65.3	8.0	23.1	53.6	W	53.6
122-22	871	1,600	10,000	I	871	1,600	197	28.5	228	33.1	8.0	38.5	66.7	W	66.7
X-167	593	1,100	10,000	H	25	77	425	61.7	740	107.4	30.2	30.7	35.9	W	35.9
X-171	704	1,300	10,000	H	25	77	678	98.3	1,060	153.7	4.1	4.1	12.1	W	12.1
X-175	871	1,600	10,000	H	25	77	441	64.0	774	112.3	4.6	4.6	9.9	W	9.9
X-168	593	1,100	10,000	H	593	1,100	259	37.6	514	74.6	29.0	29.4	33.3	W	33.3
X-172	704	1,300	10,000	H	704	1,300	408	59.2	566	82.1	4.9	12.1	42.2	W	42.2
X-176	871	1,600	10,000	H	871	1,600	202	29.3	232	33.6	5.0	25.6	63.3	W	63.3
X-180	593	1,100	20,000	H	25	77	523	75.8	907	131.5	4.8	5.0	22.6	B	35.9
X-184	704	1,300	20,000	H	25	77	589	85.4	996	144.4	1.4	1.4	7.2	W	7.2
X-188	871	1,600	20,000	H	25	77	330	47.9	661	95.9	3.1	3.1	10.4	W	10.4
X-179	593	1,100	20,000	H	593	1,100	434	63.0	736	106.7	4.5	5.1	22.1	B	0.6
X-183	704	1,300	20,000	H	704	1,300	423	61.3	567	82.3	2.2	10.4	36.3	W	36.3

[a]W, weld metal.

[b]As welded.

[c]B, base metal.

Table 8. Tensile properties of Hastelloy X welded with Hastelloy X by the shielded metal arc (SMAW) process

Test	Aging conditions: Temperature (°C)	Aging conditions: Temperature (F°)	Aging conditions: Time (h)	Aging conditions: Environment	Test temperature (°C)	Test temperature (°F)	0.2% Yield stress (MPa)	0.2% Yield stress (ksi)	Ultimate tensile stress (MPa)	Ultimate tensile stress (ksi)	Elongation (%) Uniform	Elongation (%) Total	Reduction in area (%)	Location of fracture	Weld reduction in area (%)
16694					25	77	454	65.9	784	113.7	37.0	38.3	60.8	B[a]	21.2
16695					593	1,100	251	36.4	580	84.1	38.0	38.3	43.8	B	30.0
16696	b	b			649	1,200	290	42.0	547	79.3	37.0	38.1	36.3	B	20.7
16697					760	1,400	308	44.6	450	65.2	14.0	19.0	30.0	W[c]	30.0
16698					871	1,600	253	36.7	267	38.7	5.0	18.1	36.2	W	36.2
16768	593	1,100	2,000	I	25	77	466	67.6	821	117.6		[illegible]3.7	36.0	B	3.5
16770	649	1,200	2,000	I	25	77	679	98.5	1,036	148.4		6.3	17.3	B	2.2
16772	760	1,400	2,000	I	25	77	571	81.8	809	115.9		2.5	2.4	W	
16774	871	1,600	2,000	I	25	77	391	56.0	693	99.2		5.3	5.8	W	
16769	593	1,000	2,000	I	593	1,100	305	43.6	610	87.4		22.7	34.0	B	3.3
16771	649	1,200	2,000	I	649	1,200	487	69.8	682	97.6		9.2	26.2	W	
16773	760	1,400	2,000	I	760	1,400	364	52.1	430	61.5	6.0	14.5	47.4	W	
16775	871	1,600	2,000	I	871	1,600	214	30.7	241	34.5	5.0	22.8	64.1	W	
120-9	593	1,100	10,000	I	25	77	520	74.5	872	124.8	16.6	17.9	36.9	B	0.0
120-13	649	1,200	10,000	I	25	77	747	107.0	1,117	160.0	4.6	4.6	10.2	W	
120-17	760	1,400	10,000	I	25	77	478	68.5	885	126.7	5.5	5.5	7.8	W	
120-21	871	1,600	10,000	I	25	77	344	49.2	672	96.2	7.3	7.3	9.7	W	
120-10	593	1,100	10,000	I	593	1,100	386	55.3	681	97.5	9.9	10.2	29.3	B	0.0
120-14	649	1,200	10,000	I	649	1,200	525	75.2	676	96.8	4.5	9.3	35.6	W	
120-18	760	1,400	10,000	I	760	1,400	331	47.4	420	60.2	8.0	14.8	49.1	W	
120-22	871	1,600	10,000	I	871	1,600	204	29.2	241	34.5	7.0	22.0	61.9	W	

[a]B, base metal.

[b]As welded.

[c]W, weld metal.

Table 9. Tensile properties of Hastelloy X welded with Hastelloy S filler metal by the gas tungsten arc (GTA) process

Test	Aging conditions: Temperature (°C)	Aging conditions: Temperature (F°)	Aging conditions: Time (h)	Aging conditions: Environment	Test temperature (°C)	Test temperature (°F)	0.2% Yield stress (MPa)	0.2% Yield stress (ksi)	Ultimate tensile stress (MPa)	Ultimate tensile stress (ksi)	Elongation (%) Uniform	Elongation (%) Total	Reduction in area (%)	Location of fracture	Weld reduction in area (%)
16712					25	77	456	66.2	725	105.2	38.0	40.0	69.9	B[a]	53.4
16713					593	1,100	304	44.1	548	79.5	33.0	33.5	63.7	W[b]	
16714	*c*	*c*			649	1,200	308	44.6	535	77.6	36.0	36.8	56.3	W	
16715					760	1,400	283	41.0	443	64.2	15.0	30.9	65.5	W	
16716					871	1,600	248	35.9	262	38.0	5.0	26.0	74.4	B	21.2
16784	593	1,100	2,000	I	25	77	484	69.3	845	121.0		29.6	35.4	B	16.3
16786	649	1,200	2,000	I	25	77	501	71.8	847	121.3		12.1	33.1	W	
16788	760	1,400	2,000	I	25	77	496	71.0	909	130.1		11.4	24.8	W	
16790	871	1,600	2,000	I	25	77	398	57.0	810	116.0		19.7	23.0	W	
16785	593	1,100	2,000	I	538	1,000	341	48.8	643	92.0		31.1	38.7	B	20.8
16787	649	1,200	2,000	I	649	1,200	351	50.2	624	89.3		16.3	39.1	W	
16789	760	1,400	2,000	I	760	1,400	327	46.8	474	67.8	11.0	31.2	63.7	B	11.1
16791	871	1,600	2,000	I	871	1,600	225	32.2	260	37.2	6.0	44.5	73.8	B	20.0
124-9	593	1,100	10,000	I	25	77	494	70.7	852	122.0	17.4	18.6	40.1	B	6.6
124-13	649	1,200	10,000	I	25	77	550	78.8	946	135.5	9.5	9.5	25.1	W	
124-17	760	1,400	10,000	I	25	77	472	67.6	922	132.0	13.9	13.9	23.2	W	
124-21	871	1,600	10,000	I	25	77	360	51.6	777	111.3	22.4	22.4	26.0	HAZ[d]	35.4
124-10	593	1,100	10,000	I	593	1,100	356	51.0	642	91.9	18.9	20.2	42.7	B	2.5
124-14	649	1,200	10,000	I	649	1,200	439	62.8	735	105.2	17.3	24.3	24.0	W	
124-18	760	1,400	10,000	I	760	1,400	313	44.8	467	66.8	10.0	25.5	49.0	B	15.8
124-22	871	1,600	10,000	I	871	1,600	199	28.5	249	35.7	7.0	37.6	72.2	B	7.0

[a]B, base metal.

[b]W, weld metal.

[c]As welded.

[d]HAZ, heat-affected zone.

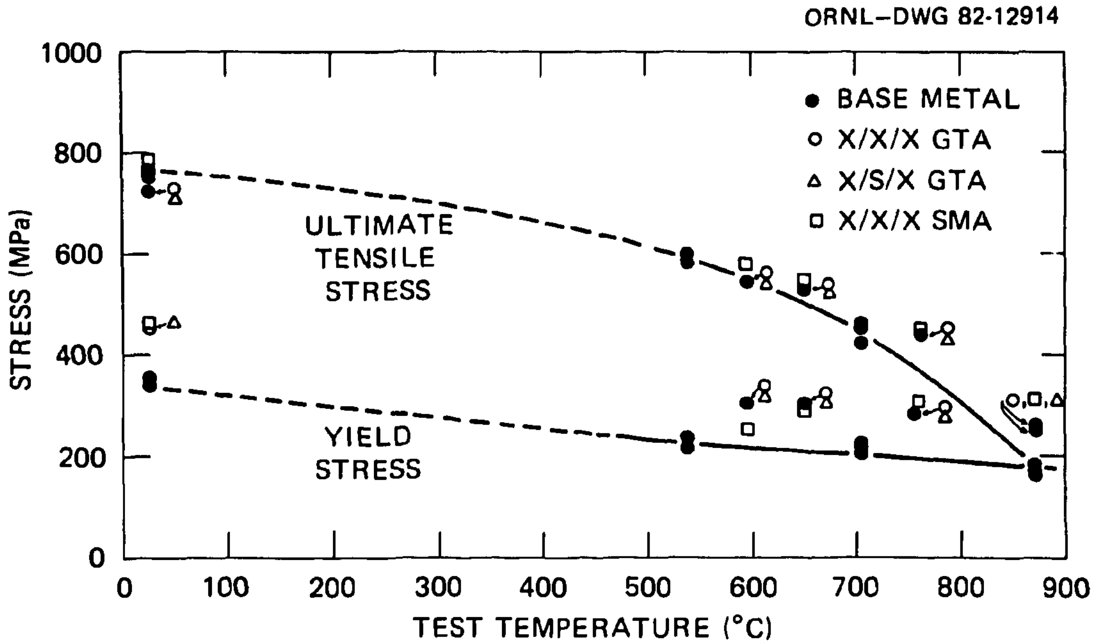

Fig. 11. Yield and tensile stresses of base metal and weldments.

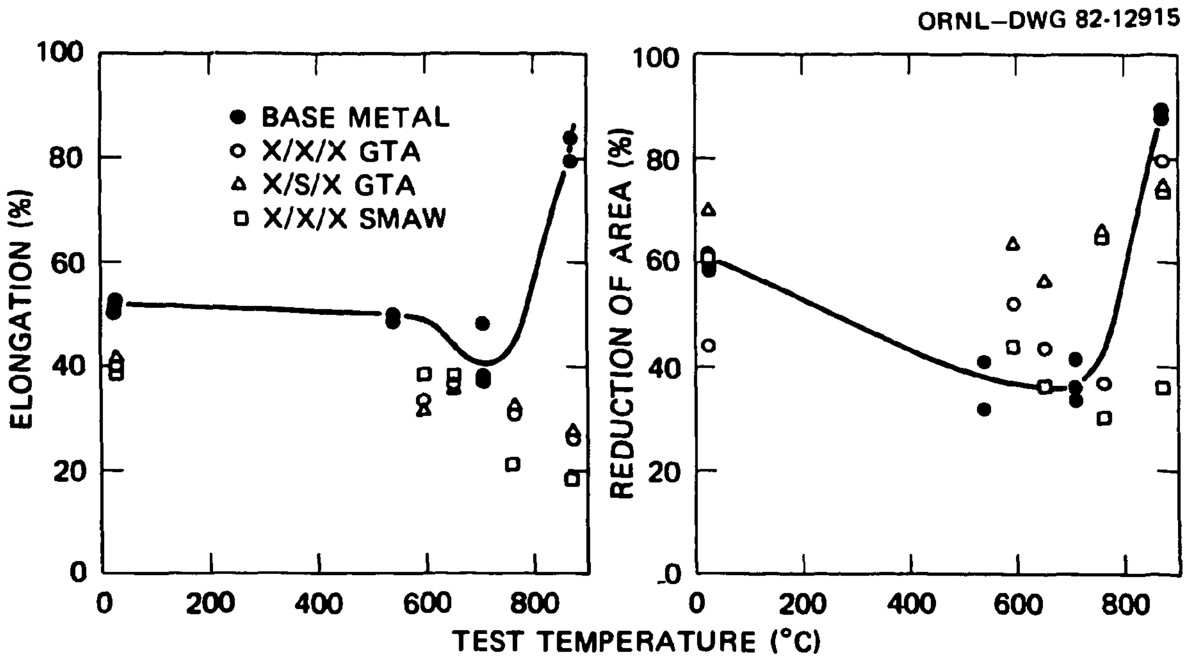

Fig. 12. Ductility parameters of Hastelloy X base metal and weldments.

of test temperatures, the difference being the greatest at the highest test temperature, 871°C. The two weldments made by the GTA process had similar elongations, but the weldment made by the SMA process had significantly lower elongation at 760 and 871°C. The reduction of area values for the weldments were generally as high as or higher than those for the base metal. One consistent trend was that, in all elevated temperature tests, the SMA weldment samples had the lowest reduction of area.

The ductility situation of the weldments is complicated by the variation in the location of failure in the base metal and the weld metal. The data in Figs. 9 and 11 indicate that the all-weld metal samples and the transverse-weld samples were stronger than the base metal so that failure would be expected to occur consistently in the weaker base metal. However, failure is more often located in the weld metal than in the base metal (Fig. 13). Because the weld metal had lower elongation at failure (Fig. 10), one would expect that samples failing in the weld metal would exhibit less elongation than would samples failing in the base metal, but this is not always the case. Note in Fig. 12 that all three weldments had very similar elongations but that failure occurred in the weld metal in two weldments and in the base metal in one weldment.

The strength properties of the three weldments are compared in Fig. 14 on the basis of tensile tests at about 25°C. The strength was essentially unchanged by aging at 593°C, decreased slightly as a result of aging at 871°C, and underwent significant strengthening from aging at 650°C. The weldment with Hastelloy S filler metal exhibited the least response to aging, and the two weldments with Hastelloy X filler metal exhibited similar responses within the scatter of the data. In some instances the strength appeared to increase with aging time, but in other cases decreases were noted.

The reduction of area measurements at 25°C are shown in Fig. 15 for the three weldments. The maximum effects were at an aging temperature of 760°C. The lowest value for the X/X/X GTA* weldment was 9.2% after aging

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*X/X/X GTA denotes base metal/filler metal/base metal in terms of Hastelloy designation.

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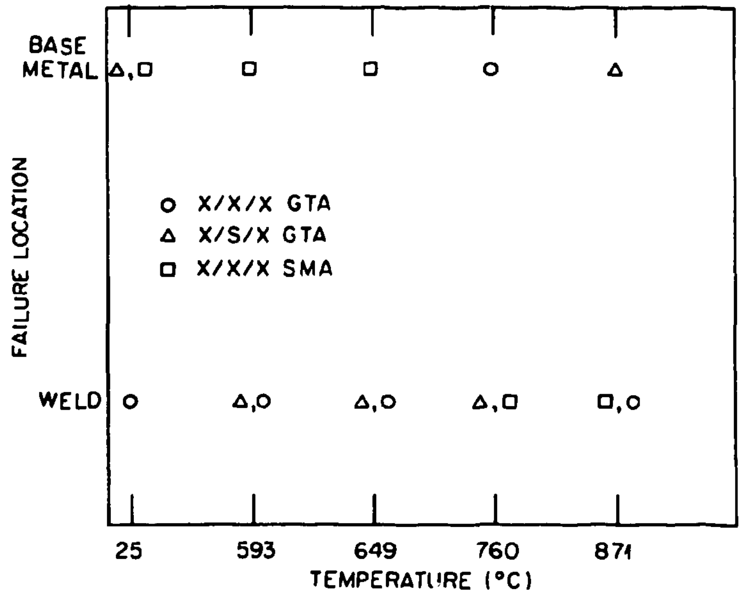

Fig. 13. Fracture location in transverse weldments does not follow a consistent pattern.

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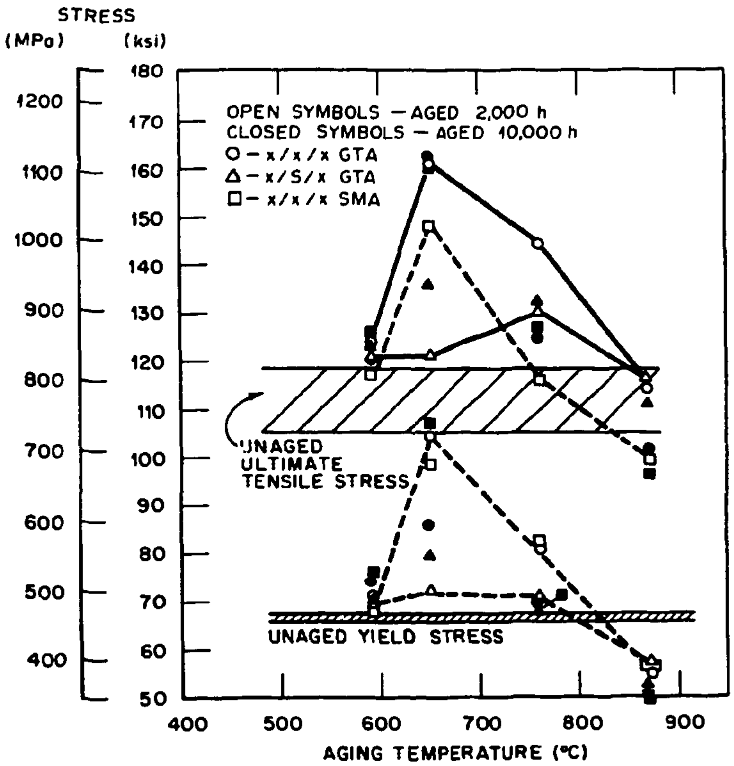

Fig. 14. Influence of aging on the yield and ultimate tensile stresses of three Hastelloy X weldments measured at 25°C.

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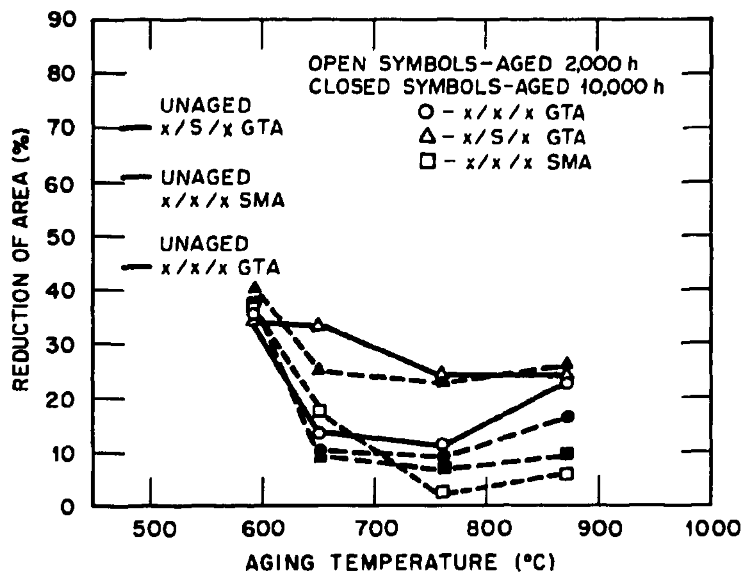

Fig. 15. Influence of aging on the reduction of area of three Hastelloy X weldments measured at 25°C.

for 10,000 h at 760°C. The weldment made with Hastelloy S filler metal exhibited the least effects of aging, with the lowest value for reduction of area being 23.0% observed after 2000 h of aging at 871°C.

Quite often the location of the fracture was changed as a result of aging, as can be evaluated from the data in Tables 7, 8, and 9. Samples of the X/X/X GTA weldment were also aged in HTGR helium for 10,000 h; the property changes in inert gas and helium can therefore be compared (Table 7). The main difference in strength was the greater strength after aging at 593°C in inert gas, compared with that after aging in HTGR helium. We have no explanation for this difference.

The elongations at facture for the samples tested at 25°C are compared in Table 10. Other than the higher elongation with aging in helium at 593°C, the elongations observed after aging at other temperatures were consistently lower for samples aged in helium. Data are also shown in Table 7 for X/X/X GTA weldment samples aged 20,000 h in helium. Note that

Table 10. Comparison of the fracture strains in tensile tests at 25°C of transverse weld samples aged for 10,000 h in inert gas and HTGR helium

Aging temperature (°C)	Elongation at rupture (%)	
	Inert environment	HTGR helium
593	18.5	30.7
650	6.1	
704		4.1
760	6.5	
871	10.6	4.6

the additional aging time at 593°C increased the strength considerably and reduced the ductility parameters. Further aging at 704 and 871°C up to 20,000 h generally caused decreases in the strength and ductility parameters compared with the samples aged for 10,000 h. The lowest ductility was obtained for a sample aged for 20,000 h at 704°C and tested at 25°C, which had an elongation of only 1.4% and a reduction of area of 7.2%. By comparison, the base metal aged and tested under the same conditions had an elongation of 8.2% and a reduction of area of 3.5% (Table 4).

4. RESULTS OF IMPACT TESTS

Impact samples illustrate even more effectively the reduction in fracture toughness of Hastelloy X with aging. As shown in Fig. 16 and Table 11, the fracture toughness is reduced appreciably by aging from 538 to 871°C in an inert environment. Although the reduction occurs in much shorter times at 871°C, the impact energy after aging at 704 and 871°C eventually gets below 13.6 J (10 ft-lb). The scanning electron micrographs in Fig. 17 for impact samples aged for 20,000 h show the transition of the fracture mode from ductile transgranular tearing in the as-received material to rather brittle intergranular fractures in the aged samples. Particularly at 704 and 871°C, the fracture path seems to follow the grain-boundary carbide network. Elemental analysis of the fracture

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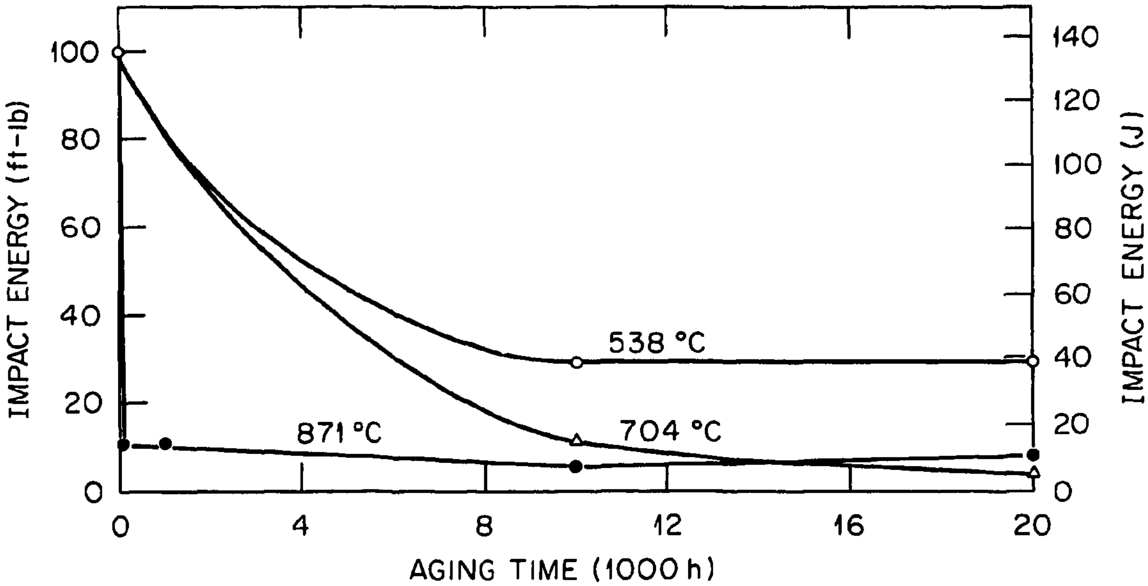


Fig. 16. Effect of aging on impact properties of Hastelloy X at 25°C.

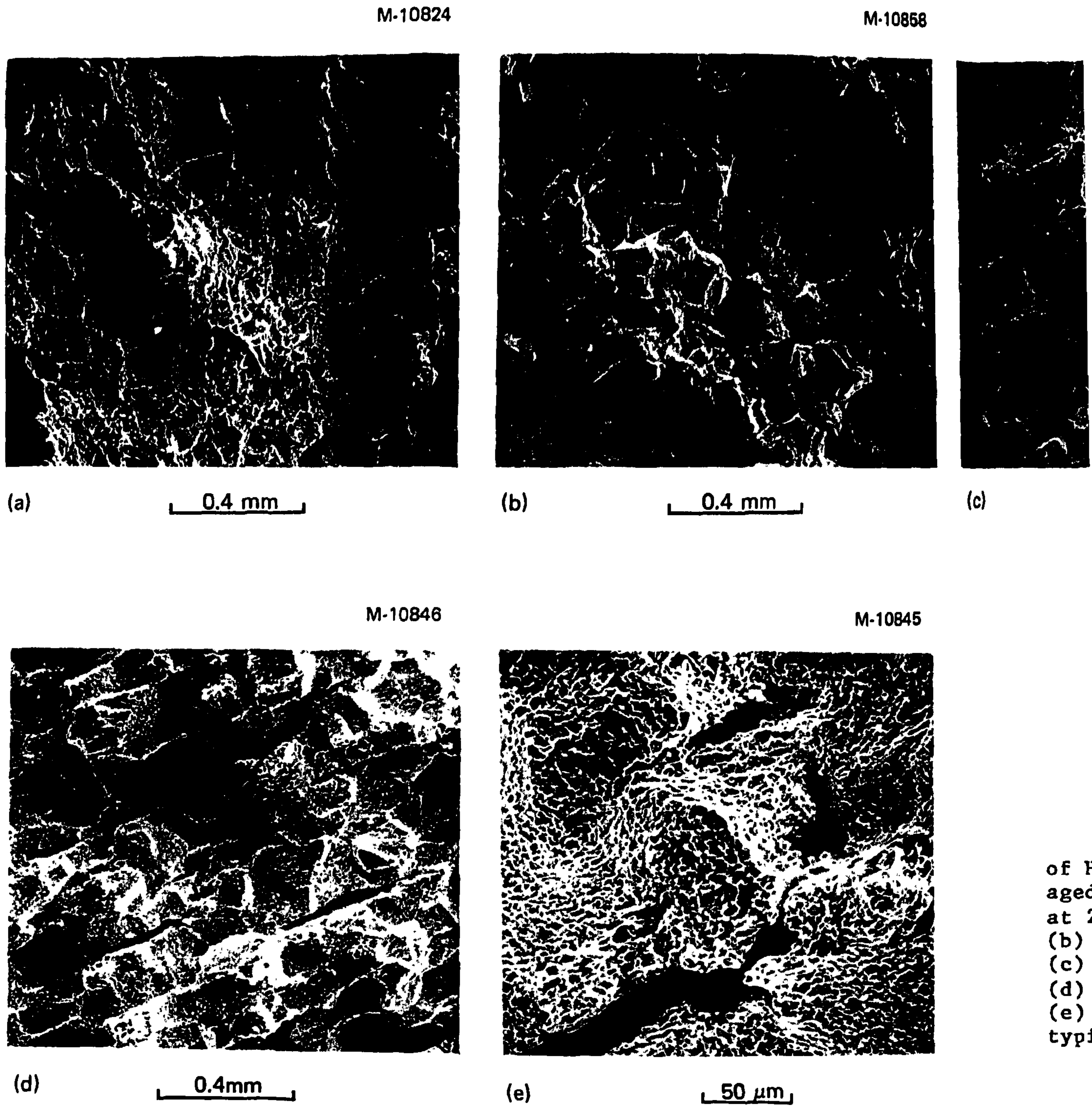
surface indicates a high concentration of molybdenum, the major constituent in the carbide. The numerous cracks running transverse to the fracture plane indicate the ease in nucleating cracks in these brittle samples. Unfortunately, duplicate samples were not aged in HTGR helium to determine if carburization would result in even lower impact values.

Table 11. Impact properties of Hastelloy X

Treatment		Environment[a]	Impact energy at 25°C	
Temperature (°C)	Time (h)		(J)	(ft-lb)
b	*b*		136, 137	100, 101
538	10,000	I	39	29
538	20,000	I	40	29.5
704	10,000	I	15	11
704	20,000	I	5	4
871	100	H	14	10.5
871	1,000	H	15	11
871	10,000	I	7.5	5.5
871	20,000	I	11	8

[a]I, inert; H, HTGR helium.

[b]As received.



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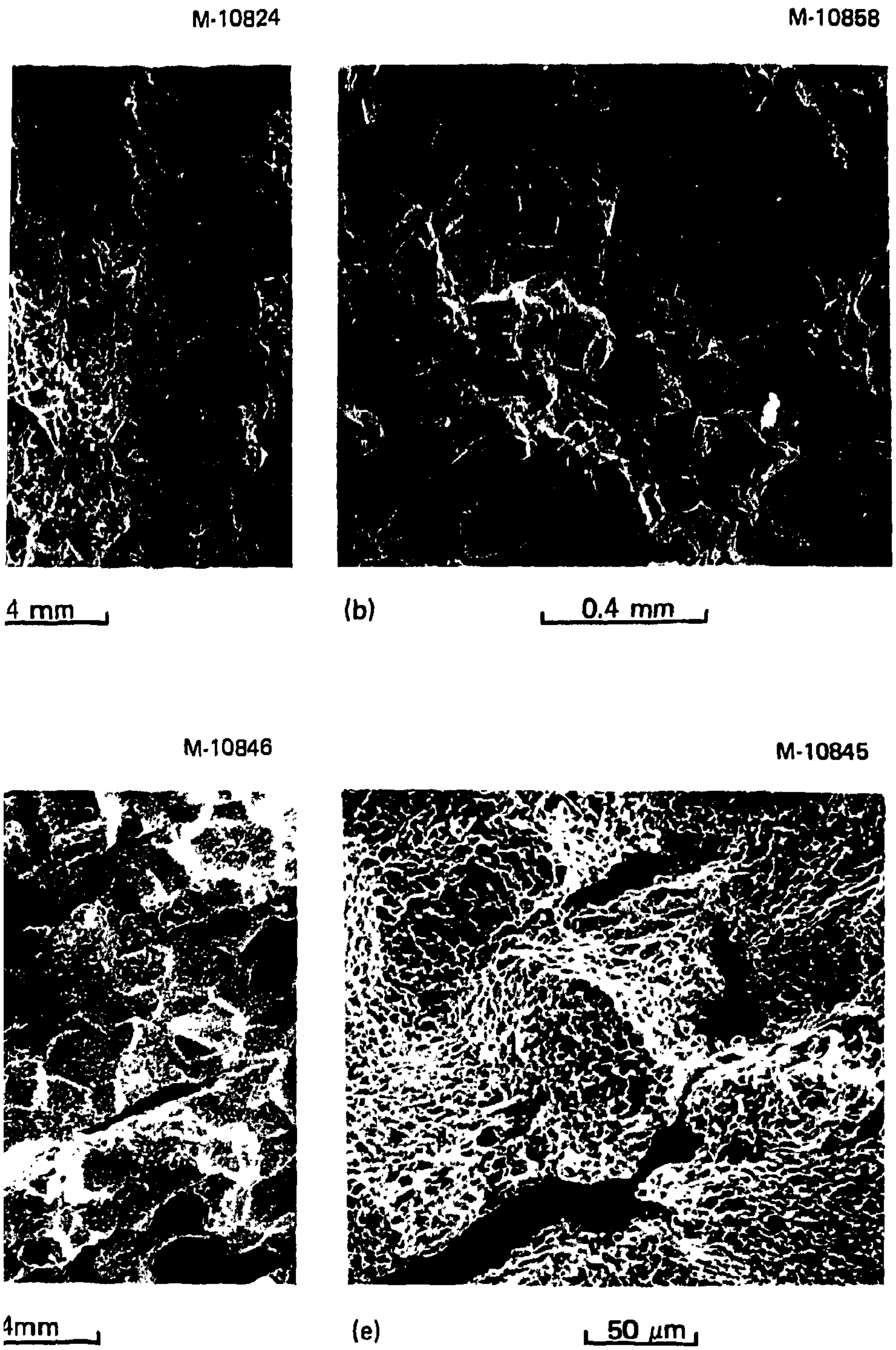

Fig. 17. Fracture surfaces of Hastelloy X impact samples aged in inert gas and fractured at 25°C. (a) As received. (b) Aged 20,000 h at 538°C. (c) Aged 20,000 h at 704°C. (d) Aged 20,000 h at 871°C. (e) Surface in (d) but also typical of (c).

5. RESULTS OF CREEP TESTS

5.1 BASE METAL

The test results of two heats of Hastelloy X tested in the as-received condition in air and HTGR helium environments are summarized in Table 12. The time to 1% strain is shown as a function of stress level in Fig. 18. The data exhibit considerable scatter at this strain level because of the inherent problems (mostly variation in ambient temperature) in measuring small elongations. For example, 1% strain corresponds to only 0.025 cm (0.010 in.) of movement, so small shifts in ambient temperature can lead to thermal expansions or contractions that appear as strains. However, the data in Fig. 18 do not show consistent effects of lot or test environment. Similar results are shown in Fig. 19 for the time to 2% strain. The scatter is considerably less than that noted in Fig. 18, but the results are not detectably influenced by lot or test environment. The stress-rupture properties are shown in Fig. 20, with rupture times to 40,000 h. As noted at lower strains, lot and test environment do not have detectable effects. The only irregularity in the data exists at 760°C after about 20,000 h, where two tests have failed and two continue. Both of the failed tests fall short of the line drawn on the basis of the rest of the data. The two continuing tests should help to determine if there is a change in the slope of the stress-rupture curve at 760°C.

The minimum creep rates for the various tests are shown in Fig. 21. These data do not indicate consistent effects of lot or test environment on the properties. The minimum creep rate applies over a very short portion of the total test time, as shown by the creep curves at most conditions, which are concave upward. At low test temperatures (e.g., 649°C) a typical creep curve will display a primary creep period in which the creep rate decelerates and will then change to a concave upward portion in which the creep rate accelerates. Thus, the so-called minimum creep rate is determined by constructing a tangent to the curve, which applies over a relatively short portion of the test. As the test temperature is

Table 12. Results of creep tests on Hastelloy X

Test	Temperature		Stress		Environment	Time (h)					Steady-state creep rate (h^{-1})	Elongation (%)		Reduction of area (%)
	(°C)	(°F)	(MPa)	(ksi)		To 1% creep	To 2% creep	To 5% creep	To tertiary	Rupture or test		Loading	Creep	
						Heat 4936								
18973	871	1,600	69	10.0	He	11	24	63	65	157	78×10^{-5}			60.4
18592	871	1,600	48	7.0	He	210	430	770	400	1,332	3.0	0.07	28.8	45.0
19773	871	1,600		7.0	Air	55	175	380	290	746	8.0		47.9	57.0
17850	871	1,600	34	5.0	Air	1,050	3,000			5,771[a]	0.62	0.09	3.7	
16126	871	1,600	34	5.0	He	3,414	4,000	5,400	2,350	6,527	0.10	0.01	14.2	12.8
17375	816	1,500	69	10.0	Air	119	400	970	690	1,905	3.4		43.7	52.5
17332	816	1,500	69	10.0	He	253	887	1,745	900	2,790	1.4	0.15	25.7	
17330	760	1,400	138	20.0	Air	18	35	95	113	297	46		52.4	71.5
16125	760	1,400	138	20.0	He	16	30	103	142	305	40		38.9	75.3
18883	760	1,400		20.0	He	12.5	25	69	140	257	71	0.08	51.2	72.2
18451	760	1,400	103	15.0	Air	65	240	830	753	2,269	4.8	0.14	41.7	70.6
16490	760	1,400	103	15.0	He	377	1,110	2,180	1,480	2,690	1.2	0.24	18.5	29.8
18450	760	1,400	69	10.0	He	1,000	8,400	19,200	8,200	19,850[a,b]	0.10		5.4	
18449	760	1,400	69	10.0	Air	875	5,200	13,100	8,300	17,929[b]	0.21	0.01	15.7	23.8
17875	760	1,400	69	10.0	He	2,500	11,500	21,200	12,000	26,497	0.10		12.8	16.6
18861B	760	1,400	69	10.0	Air	600	6,900	18,000		18,640[a]	0.13		5.1	
18879	704	1,300	207	30.0	He	20	35	69	38	228	46	0.22	46.8	71.2
15771	704	1,300	172	25.0	He	49	104	321	510	1,007	14	0.14	35.2	63.3
15058	704	1,300	138	20.0	He	113	344	1,920	1,950	4,045	1.7	0.10	21.4	5.8
15792	704	1,300	138	20.0	He	148	500	2,590	2,000	4,588	1.1	0.02	22.9	45.7
16268	704	1,300	138	20.0	Air	98	297	2,139	1,950	4,504	1.2	0.05	18.2	23.7
17376	704	1,300	103	15.0	Air	150	550	14,500	20,000	41,127	0.15		17.5	23.2
17328	704	1,300	103	15.0	He	350	5,600	15,750	11,000	21,000	0.11	0.11	20.8	27.3
18878	649	1,200	345	50.0	He	0.4	2	21.5	19	95.2	130	3.8	38.5	47.0
17863	649	1,200	207	30.0	He	375	560	1,800	2,600	4,188	2.1	0.05	22.1	53.9
16267	649	1,200	172	25.0	Air	250	700	3,900	8,750	16,528	0.48	0.36	34.7	56.0
15772	649	1,200	172	25.0	He	471	850	2,170	3,950	6,466	1.7	0.15	34.7	52.8
18150	649	1,200	138	20.0	He	1,260	4,300			35,248[c]	0.075		5.7	
17329	649	1,200	138	20.0	He	805	3,163			4,793[a]		0.07	2.3	1.3
18435	649	1,200	138	20.0	Air	1,300	3,600			22,030[a,b]	0.10		2.9	
18434	649	1,200	138	20.0	He	2,500	5,400			33,930[b,c]	0.13		9.2	
18436B	649	1,200	138	20.0	Air	1,200	3,100			21,987[c]	0.067		3.8	
18436A	649	1,200	103	15.0	Air					21,987[c]	0.0048		0.9	
						Heat 2792								
16054	871	1,600	62	9.0	He	93	197	327	205	554	9.5	0.07	34.7	68.5
18454	871	1,600	34	5.0	He	870	1,600	2,675	1,550	4,612	0.93	0.06	21.5	26.5
19834	871	1,600		5.0	Air	1,108	1,704		1,300	2,163[c]	0.82		53.2	
16031	760	1,400	152	22.0	He	7	15	38	44	159	120	0.09	56.6	80.5
19353	760	1,400		15.0	Air	35	210	950	1,000	3,295	3.9		53.2	
19938	760	1,400		15.0	He	50	217	810	1,419	2,730	6.0	0.03	43.7	63.2
19606	760	1,400		15.0	Air	40	200	1,100	800	3,353	2.6	0.22	39.8	
19392	760	1,400		15.0	Air	90	240	710	1,000	2,775	5.8	0.09	47.3	83.7
18447	760	1,400	69	10.0	He					12,017[a]	0.065		0.78	1.12
18448	760	1,400	69	10.0	Air	850	8,800			32,630[c]		0.12	7.6	

[a]Discontinued before fracture.

[b]Flat specimen.

[c]Test in progress.

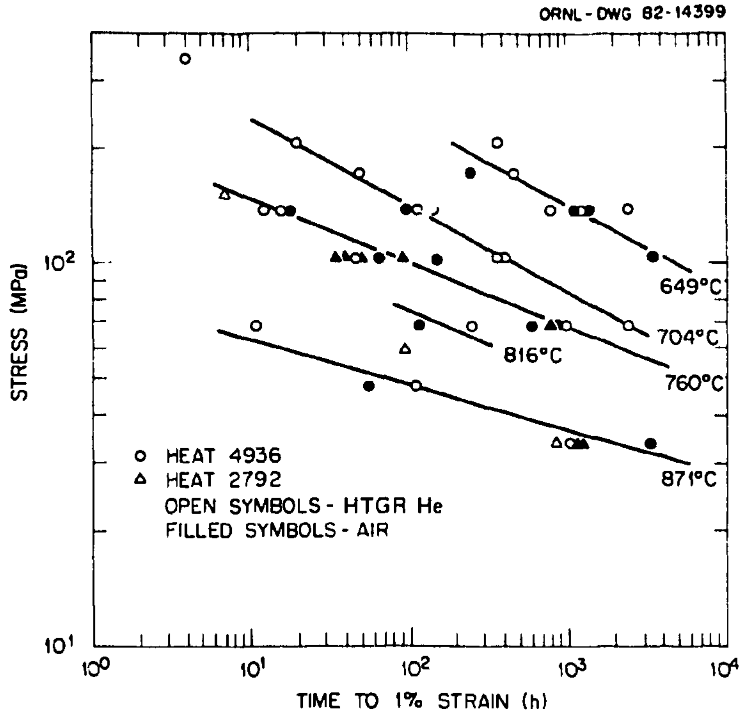

Fig. 18. Time to 1% strain as a function of stress for Hastelloy X.

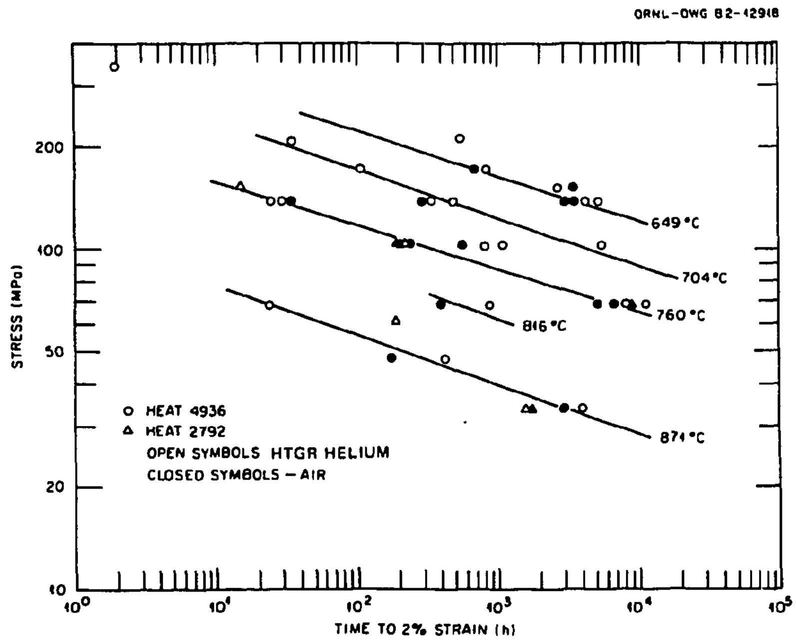

Fig. 19. Time to 2% strain as a function of stress for Hastelloy X.

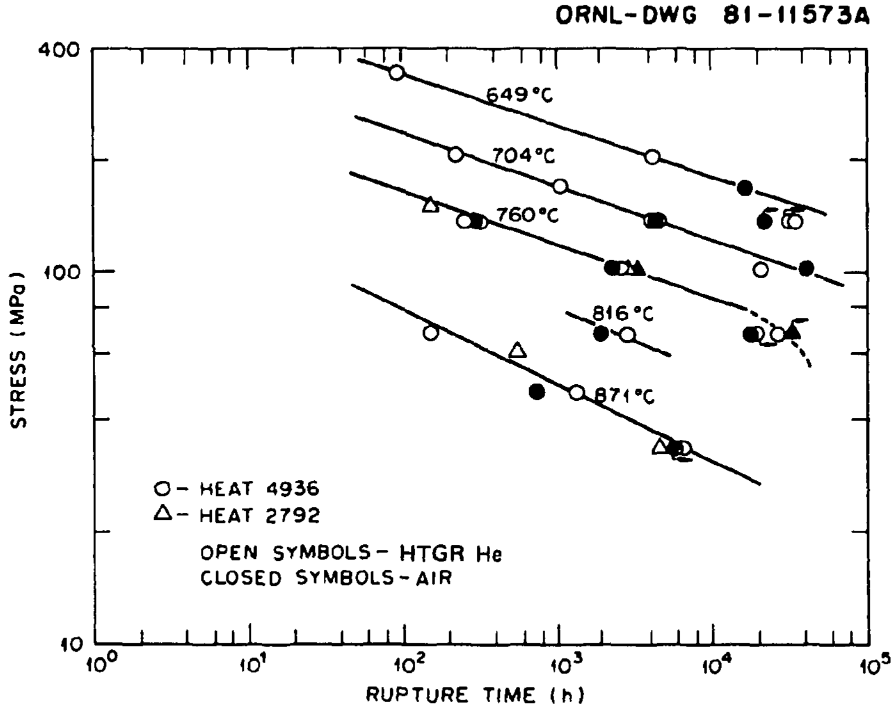

Fig. 20. Stress-rupture properties of Hastelloy X. Arrows with data points indicate that tests are still in progress.

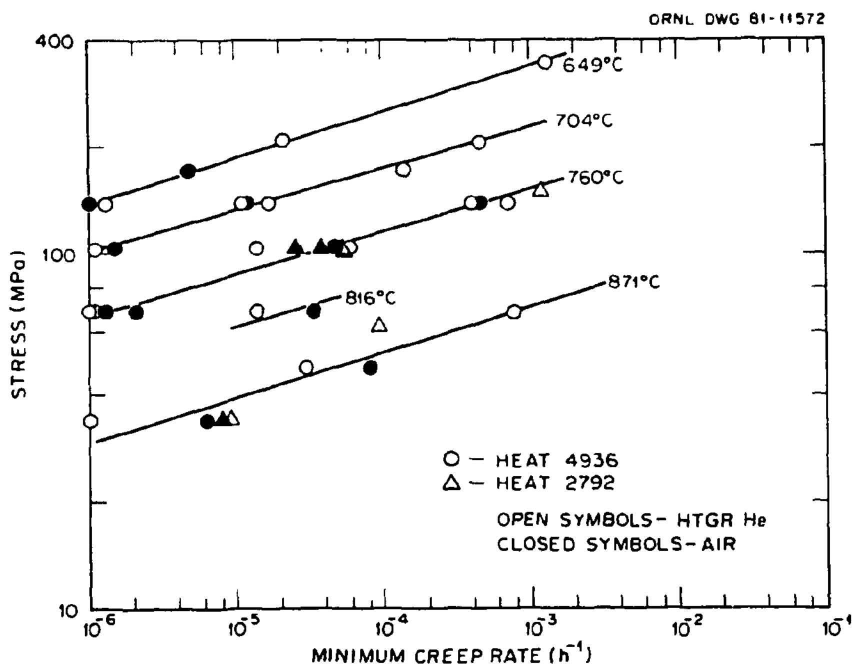

Fig. 21. Minimal creep rate for Hastelloy X under various experimental conditions.

increased, the extent of the primary creep diminishes and the creep curve becomes concave more quickly. Hence, the physical significance of "the minimum creep rate" for Hastelloy X is questionable.

Figures 22 and 23 show two correlations that define more details about the shape of the creep curve for this material. Although the individual data points in these figures are identified by lot and environment, neither variable had a detectable effect. The correlation in Fig. 22 deals with the times to 1% strain and to rupture and is affected by the experimental data scatter in measuring the 1% strain. One of the two lines in Fig. 22 represents the average of the data and indicates that the time to 1% strain is 0.067 times the rupture life. The second curve represents the lower bound of the data and indicates that the time to 1% strain is only 0.013 times the rupture life. The correlation in Fig. 23 shows that the time to tertiary creep is about three-tenths the time to rupture.

The creep strain for each test is shown as a function of rupture time in Fig. 24, in which there is a definite trend for the samples run in HTGR helium to fail at lower strains than do those tested in air. However, the lowest fracture strain was still greater than 10%. Design criteria would

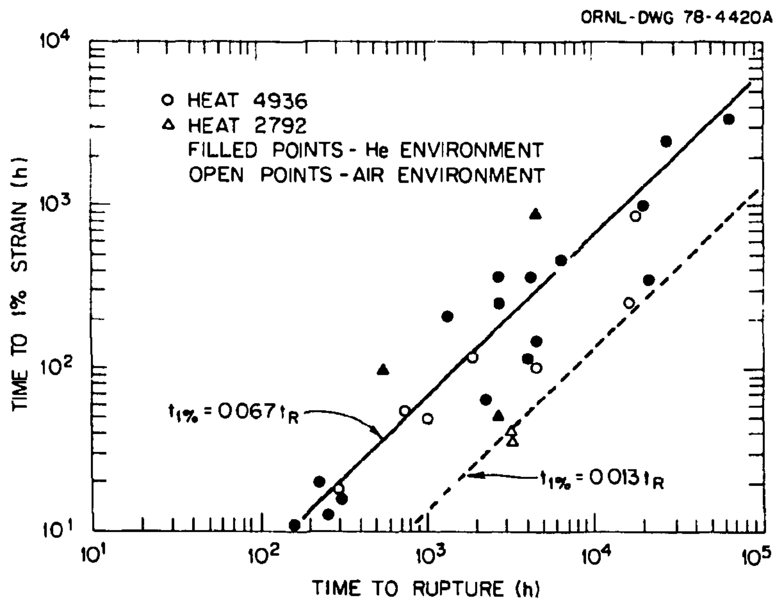

Fig. 22. Time to 1% strain as a function of rupture life for Hastelloy X.

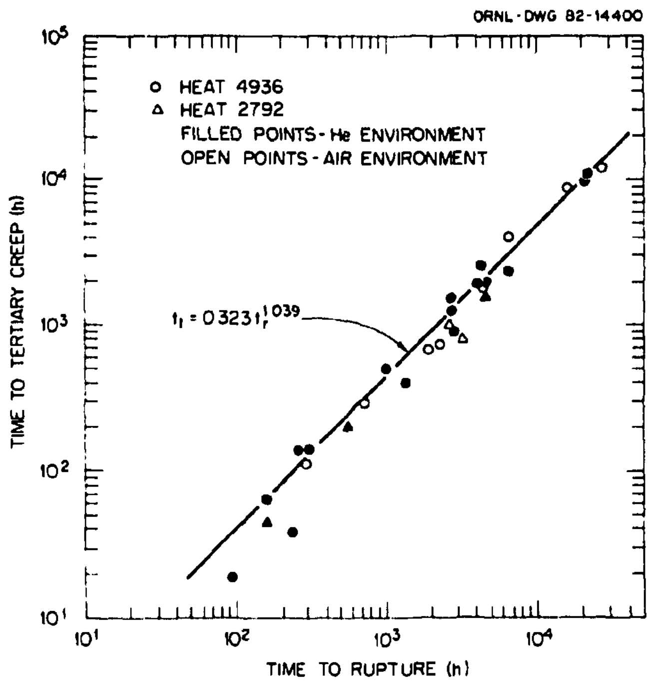

Fig. 23. Correlation of time to tertiary creep as a function of rupture life for Hastelloy X.

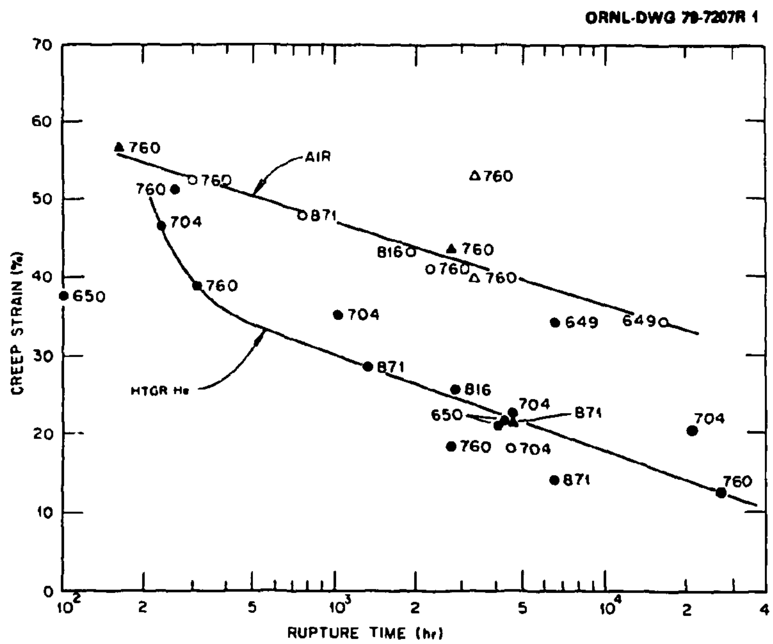

Fig. 24. Relation of creep strain to rupture life for Hastelloy X. Test run at the noted Celsius temperature.

likely limit the design strain to 1 to 2%, and the observed reduction in fracture strain during creep would likely not be important.

After testing, the creep samples were sectioned, and the entire cross section was analyzed for carbon. The entire sample was consumed in the analysis; the data in Fig. 25 therefore represent the average carbon concentration of the test samples as functions of test time and temperature. These data show that the kinetics of carburization become rather rapid above 800°C.

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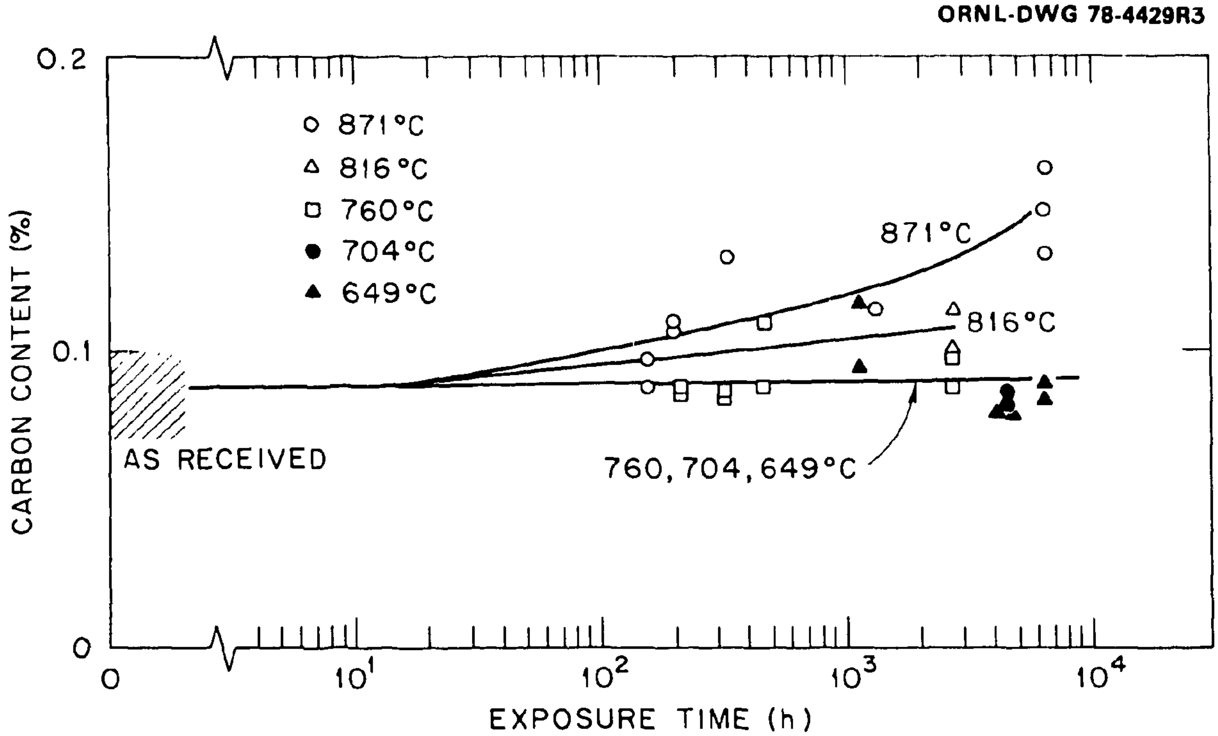

Fig. 25. Carbon content of Hastelloy X exposed to HTGR helium.

5.2 WELD SAMPLES

Some of the samples prepared by the GTA process and tested were totally of weld metal heat 4345 (Table 3). Test results for the samples tested to date are given in Table 13. Comparison of these test results with those for Hastelloy X base metal (Figs. 18, 19, 20, 21, and 24) shows

Table 13. Results of creep tests on Hastelloy X all-weld metal

(All tests in HTGR helium)

Test	Temperature (°C)	Temperature (°F)	Stress (MPa)	Stress (ksi)	Time to indicated creep strain (h) (1%)	Time to indicated creep strain (h) (2%)	Time to indicated creep strain (h) (5%)	Steady-state creep rate (h^{-1})	Time to tertiary creep (h)	Rupture life (h)	Elongation (%) Loading	Elongation (%) Creep	Reduction in area (%)
20511	593	1100	345	50	252	470	950	3.0×10^{-6}	250	2097	0.07	19.1	26.0
21592	649	1200	276	40	60	110	260	18.7	450	619	0.19	19.7	32.0
20699	649	1200	276	40	60	110	250	21.0	380	558	0.43	20.6	42.5
20698	760	1400	138	20	24	82	212	16.0	157	312		18.5	53.7

that the creep properties of the weld metal approximately equal those of the base metal. The significant variation is that the fracture elongation of the weld-metal samples is about one-half that of the base metal; however, the strains are still about 20%.

Transverse samples of the three weldments listed in Table 3 were prepared and subjected to creep tests. Some of the samples were also aged in inert gas for either 2000 or 10,000 h; the test results are given in Tables 14, 15, and 16. All samples were tested in HTGR helium. The times to 1% strain and to rupture are compared with those for base metal in Figs. 26 and 27, respectively, and the minimum creep rates are compared in Fig. 28. The results generally show that the three transverse welds have about the same creep strength; are as strong as, or stronger than, the base metal; and are affected by aging for 10,000 h only at 871°C, at which the creep strength is reduced slightly.

In the transverse weld specimens in which Hastelloy X was used as the filler metal, fracture generally occurred in the weld metal (Tables 14 and 15). In the samples welded with Hastelloy S filler metal, failure generally occurred in the base metal, although a trend exists for failure to occur in the weld metal at the highest test temperature of 871°C (Table 16). The fracture strains of all the test samples are compared with those of Hastelloy X base metal in Fig. 29. Because of the large number of variables involved, it is not surprising that there is considerable scatter in the test results. However, the fracture strains of the weldments are generally lower than those of the base metal, and almost one-half the test results range from 4 to 10%. Although test and aging temperatures are not shown in Fig. 29, the data in Tables 14, 15, and 16 show that many of the high-fracture strains occurred in samples aged and tested at 760 and 871°C. Thus, postweld heat treatments would likely be beneficial in increasing the creep fracture strain of Hastelloy X weldments. In the as-welded condition, the test results show generally that the lowest fracture strains occurred in the weldment using Hastelloy X filler wire and the SMA welding process, that the highest fracture

Table 14. Results of creep tests on gas tungsten arc (GTA) welds in Hastelloy X with Hastelloy X filler metal

(Tested in HTGR helium)

Test	Temperature (°C)	Stress (MPa)	Stress (ksi)	Condition[a]	Time to indicated creep strain (h) (1%)	(2%)	(5%)	Steady-state creep rate (h^{-1})	Time to tertiary creep (h)	Rupture life (h)	Elongation (%) Loading	Elongation (%) Creep	Reduction in area (%)	Location of fracture[b]
19397	593	345	50.0	*c*	260	450	810	3.2×10^{-5}	280	1,371	1.0	15.8	51.8	W
19421	593	345	50.0	*c*	330	520	1,030	2.6	300	2,230	0.36	17.1	36.2	W
18426	593	242	35.0	*c*	2,100	4,450	23,000	0.13	26,600	29,586	0.33	7.8	25.5	W
21552	593	345	50.0	2,000/593	170	320	680	6.3	500	1,667		22.1	56.0	W
20559	593	242	35.0	2,000/593	1,825	4,445		0.17		14,220[d]	0.36	4.0[d]		
20505	593	345	50.0	10,000/593	158	310	690	6.4	505	1,296	0.10	17.9	51.1	W
21553	593	345	50.0	10,000/593	115	235	540	8.3	420	1,151	0.43	19.1	57.7	W
18864	649	242	35.0	*c*	125	235	880	4.2	1,080	1,353	0.30	10.2	38.5	W
18427	649	207	30.0	*c*	190	470	4,250	0.53	4,025	4,404	0.003	6.5	19.4	W
21560	649	276	40.0	2,000/649	60	118	200	14	125	257	0.69	22.4	62.0	W
21550	649	207	30.0	2,000/649	1,600	2,975		0.39	2,700	4,022	0.12	8.8	38.4	W
9816	649	276	40.0	10,000/649	45	90	170	1.8	100	254	0.10	18.3	53.8	W
20509	649	207	30.0	10,000/649	875	1,400	2,150	0.88	1,100	2,421	0.11	11.7	46.5	W
19764	760	103	15.0	*c*	5,400	7,800		0.09	5,400	8,793		8.5	54.8	W
8428	760	138	20.0	*c*	3	225		0.3		477	0.40	7.1	44.1	W
20629	760	179	25.5	2,000/760						29	0.13	24.0	61.0	W
22212	760	103	15.0	2,000/760	980	1,650	2,175	0.8	1,335	2,193		7.8	18.2	W
20502	760	103	15.0	10,000/760	375	650	1,305	2.3	525	2,145		24.5	62.2	W
20497	760	138	20.0	10,000/760	13	30	60	61	35	142	0.13	27.7	69.9	W
8429	871	69	10.0	*c*	140	220	283	5.0	180	330	0.06	16.1	30.1	W
9794	871	35	5.0	*c*	3,500	6,500		0.16	5,500	10,867	0.00	5.8	4.7	HAZ
21562	871	69	10.0	2,000/871	18	30	70	55	40	148	0.01	33.9	61.3	B
9811	871	69	10.0	10,000/871	19	33	60	40	20	95.4	0.19	43.0	63.2	W

[a]Aging time (h)/aging temperature (°C) (in inert environment).

[b]W, weld metal; B, base metal; HAZ, heat-affected zone.

[c]As welded.

[d]In progress.

Table 15. Results of creep tests on shielded metal arc (SMA) welds in Hastelloy X with Hastelloy X filler metal

(Tested in HTGR helium)

Test	Temperature (°C)	Stress (MPa)	Stress (ksi)	Condition[a]	Time to indicated creep strain (h) (1%)	(2%)	(5%)	Steady-state creep rate (h^{-1})	Time to tertiary creep (h)	Rupture life (h)	Elongation (%) Loading	Elongation (%) Creep	Reduction in area (%)	Location of fracture[b]
19411	593	345	50.0	c	220	440	950	2.8×10^{-5}	290	1,435	1.4	8.8	11.1	W
19396	593	345	50.0	c	390	600	1,270	1.8	320	1,698	1.2	8.7	12.7	W
17564	593	242	35.0	c	2,300	6,200		0.11		11,689[d]	0.10	2.8		
19788	593	345	50.0	2,000/593	170	360	900	5.1	900	1,807	0.67	13.0	17.2	W
21567	593	242	35.0	2,000/593	3,100	6,150		0.20		10,853	0.20	3.3	2.8	W
20498	593	345	50.0	10,000/593	158	322	700	5.8	519	802	0.29	8.2	12.5	W
21555	593	345	50.0	10,000/593	170	370	720	5.0	550	729	0.13	6.1	11.4	W
19409	649	276	40.0	c	73	135	310	17	408	418	0.51	9.3	19.6	W
18422	649	207	30.0	c	375	2,200		0.35	1,600	2,158	0.03	3.9	11.0	W
19797	649	276	40.0	2,000/649	51	107		17	124	151		5.1	18.9	W
19798	649	207	30.0	2,000/649	880			0.70	1,050	1,084		3.4	7.2	W
20504	649	276	40.0	10,000/649	40	71	111	22	65	116	0.25	6.2	20.7	W
20506	649	207	30.0	10,000/649	880	910		64	860	915	0.16	4.1	12.7	W
18424	760	138	20.0	c	155	208		1.3	201	209	0.06	4.6	16.1	W
20554	760	138	20.0	2,000/760	66	92	127	3.0	35	136	0.05	7.9	25.0	W
22209	760	103	15.0	2,000/760	30	32		29	25	33		3.4	12.1	W
19815	760	138	20.0	10,000/760	16	31	63	54	32	102	0.24	15.0	55.4	W
20501	760	103	15.0	10,000/760						1,787	0.09	4.6	22.9	W
18425	871	69	10.0	c	155			0.20	147	157	0.03	4.0	14.2	W
19399	871	35	5.0	c	3,400	4,720		0.17	3,250	4,721	0.04	2.9	1.3	W
19813	871	69	10.0	2,000/871	16	36	83	44	71	123	0.12	18.3	51.6	W
19810	871	69	10.0	10,000/871	3	6	14	290	7.5	43.2	0.12	28.8	62.9	W

[a]Aging time (h)/aging temperature (°C) (in inert environment).

[b]W, weld metal.

[c]As welded.

[d]Discontinued before failure.

Table 16. Results of creep tests on gas tungsten arc (GTA) welds in Hastelloy X with Hastelloy S filler metal

(Tested in HTGR helium)

Test	Temperature	Stress		Condition[a]	Time to indicated creep strain (h)			Steady-state creep rate	Time to tertiary creep	Rupture life	Elongation (%)		Reduction in area	Location of fracture[b]	Reduction of area weld
	(°C)	(MPa)	(ksi)		(1%)	(2%)	(5%)	(h^{-1})	(h)	(h)	Loading	Creep	(%)		(%)
19420	593	345	50.0	*c*	430	690	1,316	1.5×10^{-6}	400	2,833		22.0	46.8	B	
18430	593	242	35.0	*c*	1,900	5,600		0.12		38,431[d]	0.10	4.9[d]			
21569	593	345	50.0	2,000/593	240	530	1,140	3.5	900	2,651	0.80	19.2	54.5	B	0.8
21559	593	345	50.0	2,000/871	45	100	300	15.0	450	1,121	1.2	23.7	55.4	B	17.0
21561	593	242	35.0	2,000/593	2,650	6,850		0.14		12,814[d]		2.8[d]			
21574	593	345	50.0	10,000/593	335	650	1,500	3.0	1,300	2,780	0.53	20.5	64.4	B	0
22210	593	276	40.0	10,000/593						3,456[d]		2.1[d]			
19425	649	276	40.0	*c*	83	124	275	12.0	115	760	0.24	30.9	58.0	B	
18431	649	207	30.0	*c*	375	770	2,300	2.1	4,300	5,455	0.13	21.6	78.7	W	
21590	649	276	40.0	2,000/649	90	160	330	11.0	200	632	0.11	28.8	74.8	B	20
21572	649	207	30.0	2,000/649	630	1,250	2,930	1.6	3,100	6,159	0.11	27.1	82.4	B	29
21577	649	276	40.0	10,000/649	130	212	400	8.0	190	619		24.8	72.8	B	11
20510	649	207	30.0	10,000/649	750	1,700	3,600	1.2	2,700	6,167		27.4	70.9	B	0.6
18432	760	138	20.0	*c*	21	49	120	38	110	326	0.18	26.3	71.6	W	
19766	760	103	15.0	*c*	142	400	1,020	3.6	680	1,866	0.02	18.1	65.3	HAZ	
20556	760	138	20.0	2,000/760	26	52	113	38	77	269	0.03	30.2	72.5	HAZ	
22213	760	103	15.0	2,000/760	265	540	1,100	3.0	590	1,655	0.03	18.5	72.5	W	
19818	760	138	20.0	10,000/760	20	40	90	48	70	256	0.57	33.7	83.4	W	
20507	760	103	15.0	10,000/760	1,164	1,597	2,487	0.44	950	3,258		20.2	77.4	W	
18433	871	69	10.0	*c*	51	80	158	16	67	198	0.20	9.8	31.7	W	
19812	871	69	10.0	10,000/871	5	9	21	200	14	79		46.8	74.4	B	

[a]Aging time (h)/aging temperature (°C).

[b]W, weld metal; B, base metal; HAZ, heat-afected zone.

[c]As welded.

[d]In progress.

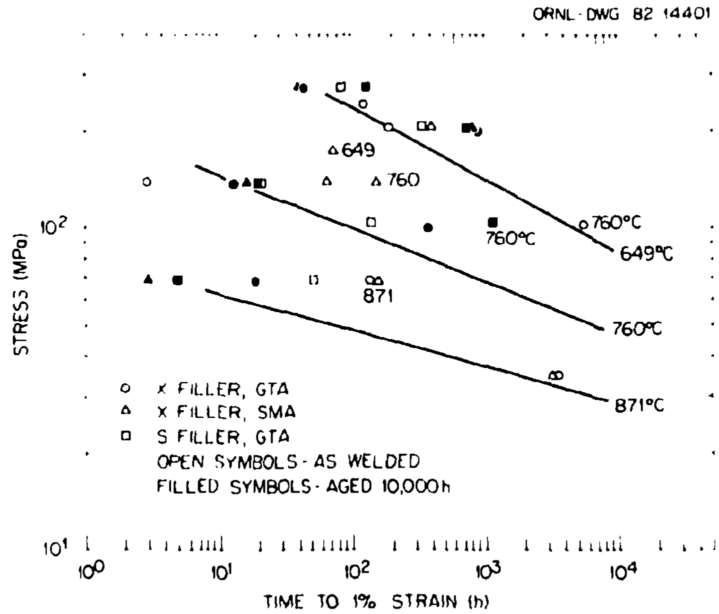

Fig. 26. Comparison of time to 1% strain for Hastelloy X and three weldments. The lines are taken from the base metal.

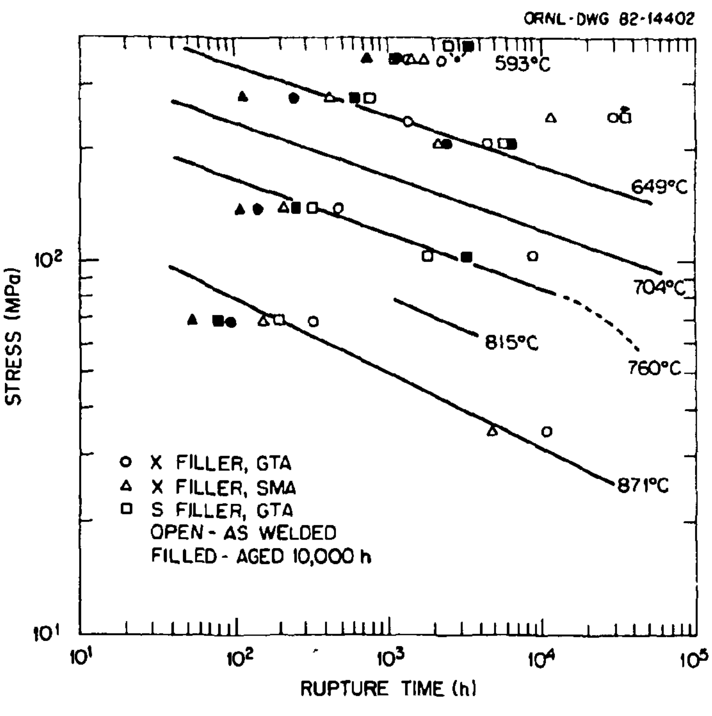

Fig. 27. Comparison of times to rupture for Hastelloy X base metal and three weldments. All tests were conducted in HTGR helium; the lines represent base metal.

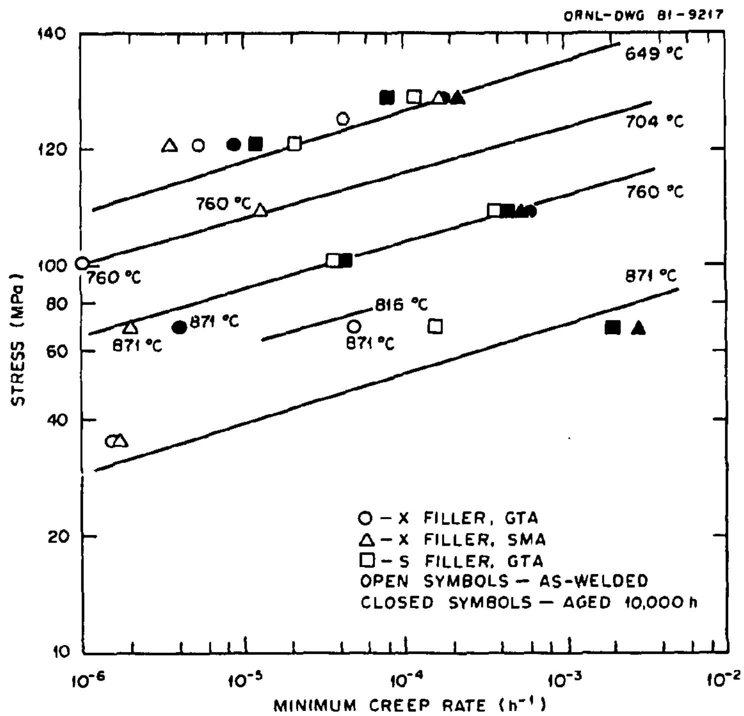

Fig. 28. Comparison of minimum creep rates of Hastelloy X base metal and three weldments. All tests were conducted in HTGR helium; the lines represent base metal.

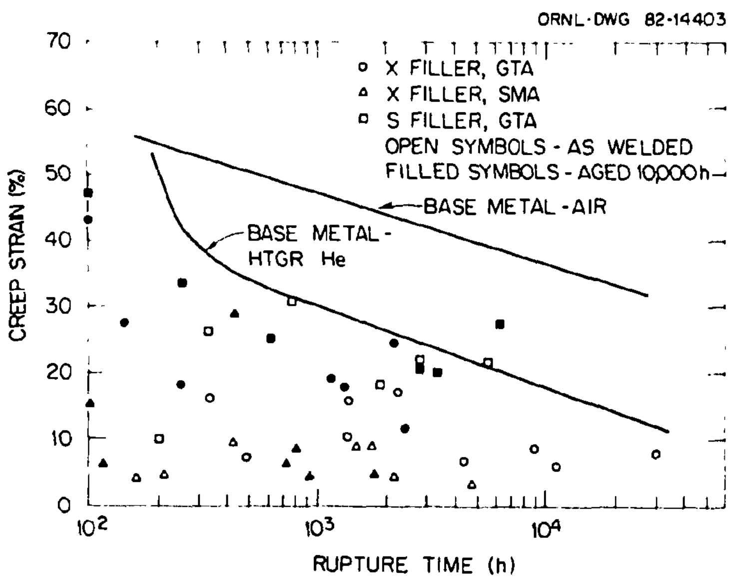

Fig. 29. Comparison of fracture strains for Hastelloy X base metal and three weldments. All weldment tests were conducted in HTGR helium.

strains occurred when Hastelloy S was the filler wire, and that intermediate values occurred when Hastelloy X filler wire and the GTA welding process were used.

5.3 AGED SAMPLES

Some additional aging experiments have been run on transverse weldments in HTGR helium and on base metal in inert gas and in HTGR helium; these test results are summarized in Tables 17 and 18. Only a few tests are now complete, and the results are rather spotty. These results and those for all-weld metal samples (Table 13) are compared with those for as-received base metal in Figs. 30 and 31. Differences in the minimum creep rate may turn out to be significant when more results became available, but the rupture life results in Fig. 31 agree very well for

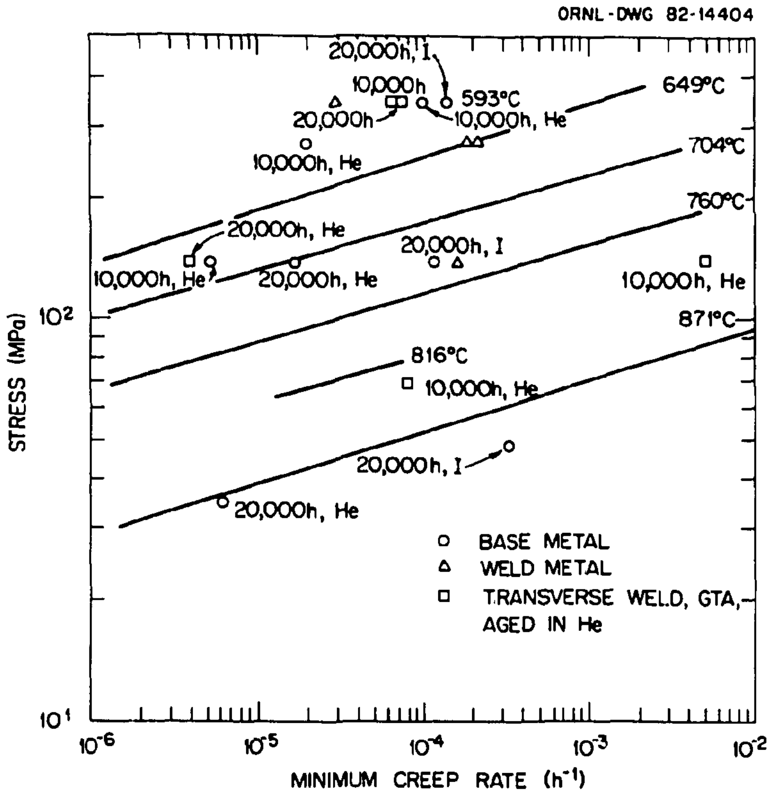

Fig. 30. Comparison of the creep rate of Hastelloy X in a number of conditions. The lines represent as-received Hastelloy X base metal.

Table 17. Results of creep tests on aged Hastelloy X base metal.

(All tests run in HTGR helium)

Test	Temperature		Stress		Condition[a]	Time to indicated creep strain (h)			Steady-state creep rate (h^{-1})	Time to tertiary creep (h)	Rupture life (h)	Elongation (%)		Reduction in area (%)
	(°C)	(°F)	(MPa)	(ksi)		(1%)	(2%)	(5%)				Loading	Creep	
21565[b]	538	1,000	345	50	20,000 h/ 538/I						18,975		13.8	
0525	593	1,100	345	50	10,000 h/ 593/H	68	165	450	10.0×10^{-5}	490	1,389	7.2	29.7	41.9
22195	593	1,100	276	40	10,000 h/ 593/H	535	1,004	2,390	2.0	2,500	7,901	2.5	32.0	46.3
22227	593	1,100	345	50	20,000 h/ 593°C/I	3	60	285	14.0	600	1,393	2.5	41.3	50.2
0529	704	1,300	138	20	10,000 h/ 704/H	1,350	2,000	2,970	0.52	1,200	3,797	0.03	17.9	41.7
2204	704	1,300	138	20	20,000 h/ 704/H	555	1,000	1,895	1.7	850	2,904	0.07	18.6	39.2
12431	704	1,300	138	20	20,000 h/ 704/I	88	150	390	12.0	282	1,711	0.06	59.1	74.9
10543	871	1,600	48	7.0	20,000 h/ 871/I	22	40	105	33	575	718		33.7	46.3
22193	871	1,600	35	5.0	20,000 h/ 871/H	515	1,750	6,300	0.63	6,250	11,226	0.6	15.5	15.7

[a]Aging time (h)/aging temperature (°C)/aging environment (I, inert; H, HTGR helium).

[b]Test in progress.

Table 18. Results of creep tests on Hastelloy X.

(Gas tungsten arc welds aged and tested in HTGR helium)

Test	Temperature (°C)	Temperature (°F)	Stress (MPa)	Stress (ksi)	Condition	Time to indicated creep strain (h) (1%)	Time to indicated creep strain (h) (2%)	Time to indicated creep strain (h) (5%)	Steady-state creep rate (h^{-1})	Time to tertiary creep (h)	Rupture life (h)	Elongation (%) Loading	Elongation (%) Creep	Reduction of area (%)	Location of fracture
0523	593	1,100	345	50	10,000 h in helium at 593°C	127	250	580	6.6×10^{-5}	275	940	2.5	14.3	48.8	Weld
2201	593	1,100	276	40	10,000 h at 593°C	85	225	580	7.2	475	6,819	0.3	11.7	39.0	Weld
2230	593	1,100	345	50	20,000 h at 593°C	1.7	3.7	7.9	500	5.4	961	0.62	14.5	46.8	Weld
0530	704	1,300	138	20	10,000 h at 704°C	1,710	2,365	2,960	0.40	1,500	12.4		15.3	61.6	Weld
2203	704	1,300	138	20	20,000 h at 704°C				0.064		3,012	0.22	9.6	44.2	Weld
0552	871	1,600	35	5.0	10,000 h at 871°C						7,126		0.6		
2186[a]	871	1,600	35	5.0	20,000 h at 871°C						11,599		5.7		
				10.0					8.0				14.8	58.6	Weld

[a]Test in progress.

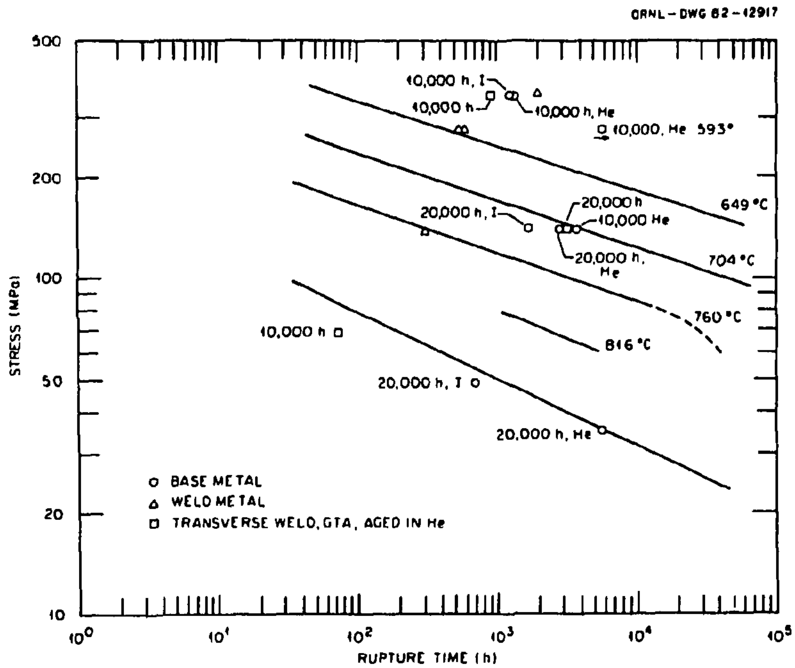

Fig. 31. Comparison of stress-rupture properties of Hastelloy X in a number of conditions. The lines represent as-received Hastelloy X base metal.

Hastelloy X under all test conditions. A scan of the fracture strains in Tables 17 and 18 indicates that typical values for weldments are 15% and that those for aged base metal are 20% and upward. Comparison with the data in Fig. 29 shows that these values for aged samples are not greatly different from those for as-received base metal and as-welded transverse weld samples.

6. SUMMARY AND CONCLUSIONS

Tensile, impact, and creep results were presented for Hastelloy X in a number of metallurgical forms. These tests involved three heats of base metal, one heat of filler metal, and one heat of Hastelloy S filler metal. Because Hastelloy X is known to change properties as a result of long-term thermal exposure, some tests were run in which samples were heated in an inert gas before being tested. In other tests samples were heated in HTGR helium containing small amounts of H_2, CH_4, and CO_2 before testing. Our tests and those of numerous other investigators have shown that these impurities in helium lead to carburization of Hastelloy X. Therefore, an important question is whether or not the property changes from thermal exposure and from carburization are additive. The creep tests in HTGR helium address the important design question of whether or not the creep strength is modified by long-term exposure to the carburizing impurties. Tests have now been run in excess of 40,000 h and are continuing. Comparative creep tests are being run in air; their most important function is to establish how the creep properties of the specific heats of Hastelloy X being tested in HTGR helium compare with the body of data already available for Hastelloy X in an air environment. This test program is ongoing, and the answers to many of the issues being studied should become clearer with time.

Our observations to date warrant at least several preliminary conclusions:

- Hastelloy X base metal tensile properties at 25°C are modified by aging at 700°C and upward. The yield and tensile strengths are increased, and the ductility is decreased. The greatest strength increase is about 25% at about 700°C. The fracture strain drops to about 10% at 700°C and remains at this level through 871°C.
- These same trends in tensile property changes occur when the aging environment is HTGR helium, but the changes are larger.
- When the tensile properties are measured at the same temperature as that at which the aging was carried out, changes in properties were not detectable for samples aged in inert gas, but strengthening and reductions in ductility were noted for samples aged at 593°C and higher in HTGR helium.
- Impact energies were measured only on samples aged in inert gas. Values of less than 13.6 J (10 ft-b) were obtained after aging only a few hours at 871°C and after about 10,000 h at 704°C.
- Suitable welds were made in Hastelloy X with Hastelloy X filler metal and either the GTA or SMA welding process. Good welds were

also obtained with Hastelloy S filler metal and the GTA welding process. Over the test temperature range of 25 to 871°C, transverse specimens of all weldments had higher yields and ultimate tensile stresses than did the base metal and had fracture strains of 20 to 40%.

- The tensile properties of weldments at 25°C responded to aging. Maximum strengthening occurred as a result of aging at 650°C, and optimum ductility reduction occured from aging at 760°C. Very little aging response was found in the samples welded with Hastelloy S. Some of the samples welded with Hastelloy X filler with the GTA welding process were aged in HTGR helium. In comparisons between samples aged in inert gas and HTGR helium, the fracture strain in a tensile test at 25°C was less for the specimens aged in HTGR helium.
- Creep tests in excess of 40,000 h on two heats of Hastelloy X base metal did not show measureable differences in creep rate between the two heats or between test environments of air or HTGR helium.
- The creep fracture strain was less for base metal samples tested in HTGR helium than for those tested in air.
- Carbon analyses of the entire cross sections of Hastelloy X creep samples showed that the kinetics of carburization increased markedly above 800°C.
- The creep curves for Hastelloy X are concave upward and do not have a long period of linear secondary or minimum creep. For example, only 6% of the time to rupture was required to reach 1% creep strain, and about 30% of the time to rupture was required to reach tertiary creep.
- Creep tests on weldments showed that the creep curves were not detectably different for transverse weldment and base metal samples. The main difference was the general failure of weldments at a lower strain. Strains of 4 to 10% were commonly noted for SMA welds of Hastelloy X with Hastelloy X filler metal and of 10 to 20% for the other two weldments. Aged samples often exhibited higher fracture strains, indicating that better properties could likely be obtained with a postweld heat treatment.

- Creep tests on a variety of samples involving base metal and transverse welds aged to 20,000 h in inert gas and HTGR helium showed very little effect on the creep response of Hastelloy X.

7. ACKNOWLEDGMENTS

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