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EVALUATION OF ADVANCED ALLOYS FOR GAS-COOLED REACTORS

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H. E. McCoy

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Prepared for
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EVALUATION OF ADVANCED ALLOYS FOR GAS-COOLED REACTORS*

H. E. McCoy

ABSTRACT

Mechanical property tests were performed on several alloys potentially useful for high-temperature gas-cooled reactor applications. These alloys included several with the basic composition of Inconel 617 but with variations in the amounts of Cr, Ti, and Al. The strength was not a detectable function of chromium content, but the extent of aging was reduced by reducing the chromium content. The addition of titanium seemed effective in reducing the extent of carburization. Very attractive properties for some special applications were found in IN-519, an iron-base cast alloy. Cabot Corporation alloy 214 was evaluated briefly and found not to have very attractive properties because of low creep strength, particularly in the weld metal, which both aged and carburized. Alloys 911 and 912 were provided by GA Technologies for our evaluation. They had excellent creep strength at 850°C, but at 950°C commercial Inconel 617 had higher creep strength. The two alloys seemed to be reasonably resistant to carburization.

The results from this study are compared with those obtained from other studies for other alloys.

INTRODUCTION

Many types of gas-cooled reactors have been proposed at various times by different study groups. The reactors vary in details of the design, but the parameters of primary concern to the materials specialist are the operating temperatures. In some systems the peak metal temperatures are about 800°C, and in more advanced systems the peak metal temperatures are 1000°C or greater. A common element in all these systems is that the service environment is pressurized helium that has been exposed to graphite and contains small amounts of hydrogen, methane, and carbon monoxide and even lesser amounts of nitrogen, carbon dioxide, and moisture. These

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impurities make the otherwise inert helium carburizing to the structural metal. This ingress of carbon may or may not alter the mechanical properties of the metal.

In the past few years, we have performed rather extensive mechanical property studies of candidate materials such as Hastelloy X and Inconel 617 and lesser studies of Inconel 618, HD 556, and Incoloy 802. Several alloy compositions have been studied very briefly over this same period because they seemed to offer some improvement in creep strength, to offer improved resistance to carburization, or to provide knowledge about the effects of particular alloy additions. The alloys involved in this study included IN-519, chemical modifications of Inconel 617, Cabot Corporation alloy 214, two Ni-Cr-Mo alloys, and modified Hastelloy N. In many cases the thoroughness of the work was limited by insufficient test materials or by learning in a few tests that the alloys were not worthy of further evaluation for this application. The findings for each alloy will be presented.

EXPERIMENTAL DETAILS

MATERIALS

The test materials involved in this program are described in Table 1.

Three heats of modified Inconel 617 were obtained from Teledyne Allvac in the form of plate 1.3 cm thick. There was sufficient material to prepare test welds. The filler wire was prepared by sawing and swaging strips of each heat.

Six laboratory melts of modified Inconel 617 were made at ORNL (alloys 800 through 805) with variations in Cr, Ti, and Al. Only small quantities of material were available, and the studies on these alloys were quite limited.

The alloy 214 base metal and filler wire were procured from Cabot in the hot-finished condition. There was sufficient material to make test welds and Charpy samples.

IN-519 is a reformer alloy and is usually centrifugally cast. In its usual formulation, it contains 1.5% niobium, but one heat was made

Table 1. Chemical and physical data for test materials

Heat	Form [cm (in.)]	Source	Chemical composition (%)										
			Ni	Fe	Cr	Mo	Co	Mn	Si	Ti	Al	C	Other
			Modified Inconel 617										
492	1.3 × 10.2 (0.50 × 4.0)	Teledyne Allvac	Bal	0.07	22.74	9.43	12.10	0.03	0.07	1.98	0.04	0.059	
493	1.3 × 10.2 (0.50 × 4.0)	Teledyne Allvac	Bal	0.03	16.19	9.26	12.21	0.03	0.07	1.75	0.05	0.051	
494	1.3 × 10.2 (0.50 × 4.0)	Teledyne Allvac	Bal	0.03	12.44	9.03	12.22	<0.01	0.06	1.79	0.03	0.066	
800	0.95 (0.375) rounds	ORNL	Bal		22	9	12			2	0.1	0.08[a]	
801	0.95 (0.375) rounds	ORNL	Bal		22	9	12			2	0.5	0.08[b]	
802	0.95 (0.375) rounds	ORNL	Bal		22	9	12			1	0.1	0.08[c]	
803	0.95 (0.375) rounds	ORNL	Bal		22	9	12			1	0.5	0.08[d]	
804	0.95 (0.375) rounds	ORNL	Bal		16	9	12			1	0.5	0.08[e]	
805	0.95 (0.375) rounds	ORNL	Bal		12	9	12			1	0.5	0.08[f]	
			Cabot Alloy 214										
7497	1.3 (0.5) plate	Cabot Corp.	Bal	2.54	15.90	<0.1	<0.10	0.2	<0.1		4.3	0.03	Y, 0.01
7290	0.40 (0.156) wire	Cabot Corp.	Bal	2.59	16.03		<0.10	0.17			4.2	0.04	Y, 0.016
			IN-519										
2356	1.3 (0.5) rounds	Certified Alloy Products	25.3	Bal	24.0	0.78		0.37	1.89	0.08	0.02	0.39[g]	Nb + Ta, 1.5
2357	1.3 (0.5) rounds	Certified Alloy Products	26.0	Bal	24.0	0.57		0.40	2.0	1.83	0.09	0.037	Nb + Ta, <0.1
			Special alloys GA 911 and GA 912										
911	1.3 (0.5) rounds	GA Technologies	Bal		8	10				2	2	298[h]	
912	1.3 (0.5) rounds	GA Technologies	Bal		8					2	2	350[h]	W, 10

[a]ORNL analysis 904 ppm.
[b]ORNL analysis 869 ppm.
[c]ORNL analysis 863 ppm.
[d]ORNL analysis 860 ppm.
[e]ORNL analysis 908 ppm.
[f]ORNL analysis 917 ppm.
[g]ORNL analysis 3000 ppm.
[h]ORNL analyses in ppm.

with 1.8% titanium instead of niobium. All of the IN-519 used in this study was mold cast as 1.3-cm-diam rods and hence would not have a microstructure typical of centrifugally cast material. However, both forms should react about equally with the test gas.

Small quantities of alloys GA 911 and 912 were provided by GA Technologies for evaluation. The alloys were in the solution-annealed and quenched condition, which involved 1125°C for 10 h for alloy 911 and 1125°C for 30 h for 912. Both alloys were reported by GA Technologies to have a grain size of approximately 250 μm.

TEST SPECIMENS

The configuration 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 setscrews to the two grooves, which have an included angle of 100°.

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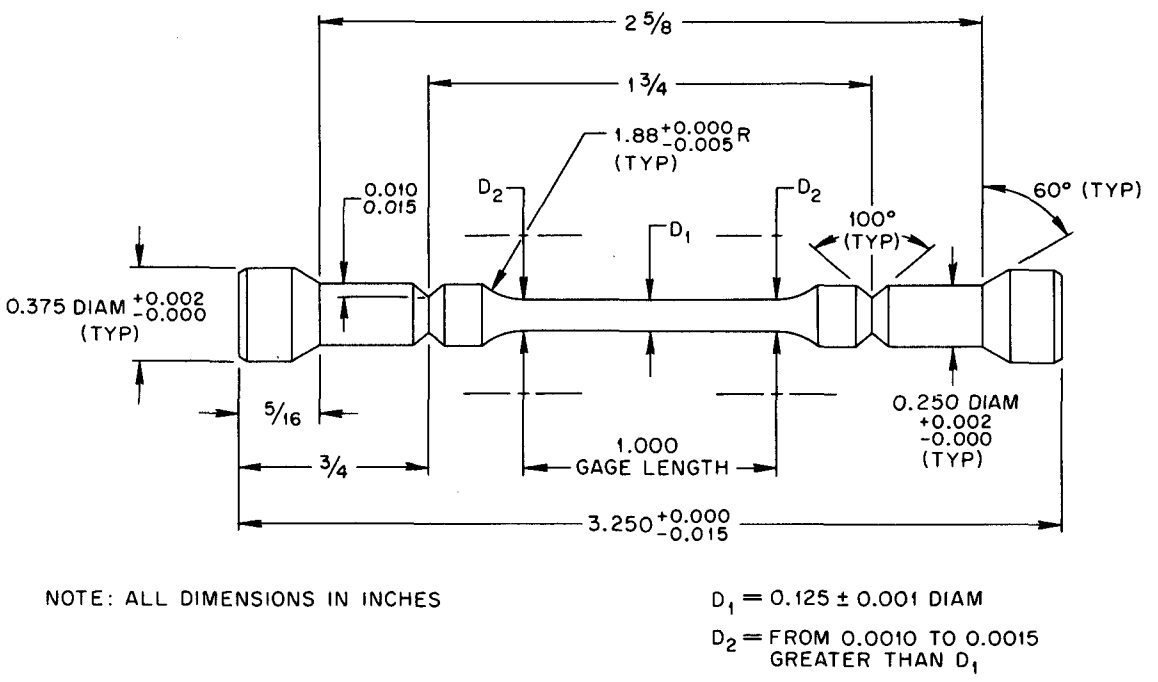

Fig. 1. Details of creep specimens for environmental tests. To convert dimensions to millimeters, multiply by 25.4.

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 each specimen spanned the weld 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.

TESTING EQUIPMENT

The creep testing chambers used in this study were described in detail previously.[1] Most are made of 51-mm (2-in.) schedule 40 type 304L stainless steel pipe, but a few chambers, operated at 871°C, are made of aluminum oxide. Neoprene U-cups are used to seal between the pull rods and the chamber and also to seal the four extensometer rods that exit the bottom of the chamber.

Some specimens aged in inert environments at 538, 704, and 871°C were simply stacked in metal retorts, which were later evacuated, filled with an inert gas, and welded shut. Specimens were aged about 20,000 h in high-temperature gas-cooled reactor (HTGR) helium in stainless steel retorts. Aging is continuing in these retorts at 593 and 704°C, but the retort operating at 871°C was replaced with an aluminum oxide retort and the specimens simply stacked in place. (The term "HTGR helium" is further abbreviated as "HTGR-He" in the rest of this report. It refers to a gas mixture, defined in the following subsection, that approximates the composition of the impure helium in an operating HTGR.)

TEST ENVIRONMENT

The test gas (HTGR-He) is premixed by the Matheson Company, Inc. It is received in pressurized cylinders and 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 testing chamber and either returned to a sample manifold or vented. The gas stream can be passed through a gas chromatograph to monitor moisture before or after it passes through the testing chamber. The gas flow to each chamber is maintained at 15 to 100 cm^3/min, with the criterion being to use a flow

rate high enough to keep the gas stream from being detectably depleted in reactants. The helium composition in the testing 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 hydrogen 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 against a certified standard prepared by the Matheson Company, Inc., and weekly readings are made routinely on each machine. The 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 startup 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. All impurities were initially high, but 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.

TEST RESULTS

MODIFIED INCONEL 617 ALLOYS 492, 493, AND 494

Source

These three alloys were prepared by Teledyne Allvac; their chemical analyses are given in Table 1. The alloys each have a nominal additive of 2% titanium compared with only a few tenths percent for standard Inconel 617. Standard Inconel 617 contains 22% chromium, and the chromium concentration was 22.7, 16.2, and 12.4% for alloys 492, 493, and 494,

respectively. The proportions of the remaining chemical elements fall closely within the ranges specified for Inconel 617. The melts were each about 90.9 kg (200 lb). The melting sequence consisted of induction melting and vacuum arc remelting. The 10.2-cm-diam (4-in.) castings prepared by this sequence were homogenized 4 h at 1150°C and hot-rolled to 1.3 cm (0.500 in.) thick by 10.2 cm (4.0 in.) wide. They received some further conditioning before shipping.

Strips 1.3 cm (1/2 in.) square were sawed and swaged to obtain weld wire. Three types of test specimens were made: entirely base metal, transverse with weld metal in the center of base metal, and entirely weld metal.

Tensile Test Results

Tensile tests were run on alloy 492 in several metallurgical conditions, and the results are summarized in Table 2. Most of the samples were annealed 1 h at 1177°C before testing, and the results for base metal and transverse welds are shown in Fig. 2. Alloy 492 has the same nominal composition as Inconel 617 plus about 2% titanium. The yield strength does not change much with test temperature, but the ultimate tensile stress decreases precipitously above 760°C. The transverse weld samples in all cases failed in the weld metal at a stress lower than that of the base metal.

Table 2 shows test results for alloy 492 after several other treatments. The material as received was heavily worked, and it had yield and ultimate tensile strengths above those of the material annealed 1 h at 1177°C. A sample of as-received material with a transverse weld had lower strength than the as-received material, and it failed in the weld. Three base metal samples were annealed at 1177°C and aged 12,500 h in HTGR-He, one each at 593, 704, and 871°C. Tensile tests at 25°C showed strong evidence of an aging reaction at 704 and 593°C and very little change in the sample aged at 871°C. As-received samples were aged for 20,500 h in HTGR-He at 593, 704, and 871°C. Testing at 25°C revealed a relaxation of the strength level that was greatest at the highest aging temperature.

The ductility of alloy 492 was quite low in the as-received condition, reflecting the large amount of residual cold work. The fracture strain

Table 2. Tensile properties of modified Inconel 617 alloy 492

Aging temperature		Test temperature		0.2% Yield strength		Ultimate tensile strength		Elongation (%)		Reduction of area (%)	Specimen type[a]	Failure location[a]
(°C)	(°F)	(°C)	(°F)	(MPa)	(ksi)	(MPa)	(ksi)	Uniform	Total			
						As received						
		25	77	1655	240.1	1746	253.2	0.5	0.8	39.3	B	
		25	77	518	75.2	721	104.6	9.8	11.5	22.3	TW	W
						Annealed 1 h at 1177°C						
		25	77	357	51.8	855	124.0	53.3	56.9	61.4	B	
		538	1000	207	30.0	698	101.2	50.7	52.8	57.1	B	
		649	1200	194	28.2	722	104.6	52.7	56.5	40.9	B	
		760	1400	183	26.6	689	100.0	54.2	57.1	47.4	B	
		871	1600	212	30.8	308	44.6	9.6	67.6	77.7	B	
		25	77	348	50.4	786	114.0	45.4	49.7	62.6	TW	W
		649	1200	189	27.4	623	90.3	46.7	47.8	42.8	TW	W
		760	1400	199	28.8	507	73.6	27.1	39.8	38.3	TW	W
		871	1600	205	29.8	283	41.1	5.7	51.7	68.9	TW	W
						Annealed 1 h at 1177°C, aged 12,500 h in HTGR-He						
593	1100	25	77	505	73.2	1006	145.9	42.3	42.8	35.7	B	
704	1300	25	77	645	93.6	1070	155.2	22.0	22.0	20.9	B	
871	1600	25	77	367	53.2	880	127.6	34.0	35.2	23.9	B	
						As received, aged 20,500 h in HTGR-He						
593	1100	25	77	969	140.6	2613	379.0	13.6	14.4	26.3	B	
704	1300	25	77	592	85.9	1101	159.7	27.0	29.2	45.5	B	
871	871	25	77	474	68.7	1001	145.2	37.4	40.2	58.3	B	

[a]B = base metal, TW = transverse weld, W = weld metal.

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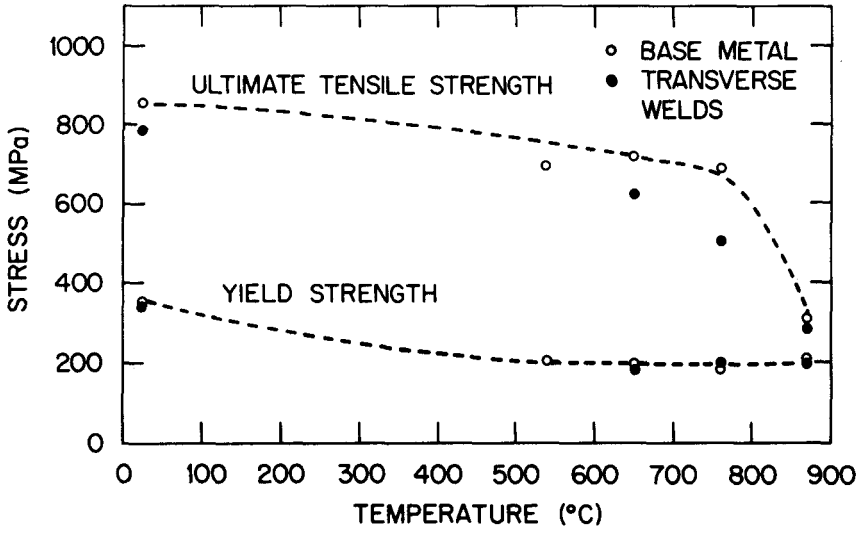

Fig. 2. Tensile properties of modified Inconel 617 alloy 492 annealed 1 h at 1177°C.

after annealing at 1177°C was 20% or greater even after aging. Thus the fracture strain of the alloy looks good in the annealed condition, but it is reduced by aging. Data for longer aging times are needed.

The tensile properties of alloy 493 are given in Table 3 and in Fig. 3. This alloy contains only 16% chromium compared with 22% for alloy 492. After annealing 1 h at 1177°C the tensile properties are very similar to those of alloy 492. Welds were consistently weaker than the base metal, and transverse weld specimens failed in the weld. Alloy 492 was quite hard as received, and welding caused localized softening. Aging the annealed material for 12,500 h in HTGR-He appeared to cause an aging reaction, with the strongest response at 593°C (compared with 704°C for alloy 492). Aging at 871°C did not cause any hardening. Aging the as-received material caused relaxation, and the largest effect was noted at the highest aging temperature of 871°C.

The fracture strains for alloy 493 were quite good except for those of the heavily worked as-received material.

Tensile data for alloy 494 are given in Table 4 and Fig. 4. This alloy contains only 12% chromium (compared with 22% for alloy 492 and 16% for alloy 493), but the tensile properties are about the same for all

Table 3. Tensile properties of modified Inconel 617 alloy 493

Aging temperature		Test temperature		0.2% Yield strength		Ultimate tensile strength		Elongation (%)		Reduction of area (%)	Specimen type[a]	Failure location[a]
(°C)	(°F)	(°C)	(°F)	(MPa)	(ksi)	(MPa)	(ksi)	Uniform	Total			
						As received						
		25	77	1505	218.3	1597	231.7	1.0	2.4	51.8	B	
		25	77	476	69.0	799	115.9	22.3	23.8	40.6	TW	W
						Annealed 1 h at 1177°C						
		25	77	318	46.1	869	126.0	46.7	51.4	53.8	B	
		538	1000	194	28.2	687	99.6	53.2	58.6	56.9	B	
		649	1200	183	26.6	686	99.5	56.7	59.6	45.3	B	
		760	1400	179	26.0	554	80.3	28.9	61.1	47.3	B	
		871	1600	209	30.3	300	43.5	6.0	81.0	90.1	B	
		25	77	299	43.3	763	110.7	48.5	53.3	57.8	TW	W
		649	1200	171	24.8	573	83.2	66.6	41.2	37.0	TW	W
		760	1400	194	28.2	511	74.2	25.2	33.8	60.3	TW	W
		871	1600	190	27.5	271	39.3	4.4	56.4	63.3	TW	W
						Annealed 1 h at 1177°C, aged 12,500 h in HTGR-He						
593	1100	25	77	510	73.9	976	141.7	36.4	36.7	33.2	B	
704	1300	25	77	371	53.8	870	126.2	38.5	38.6	32.0	B	
871	1600	25	77	312	45.2	821	119.2	52.9	56.8	65.0	B	
						As received, aged 20,500 h in HTGR-He						
593	1100	25	77	1628	236.2	1682	244.1	2.2	4.2	22.0	B	
704	1300	25	77	980	142.1	320	190.5	10.5	11.5	32.9	B	
871	1600	25	77	465	67.5	992	144.0	36.5	38.5	52.4	B	

[a]B = base metal, TW = transverse weld, W = weld metal.

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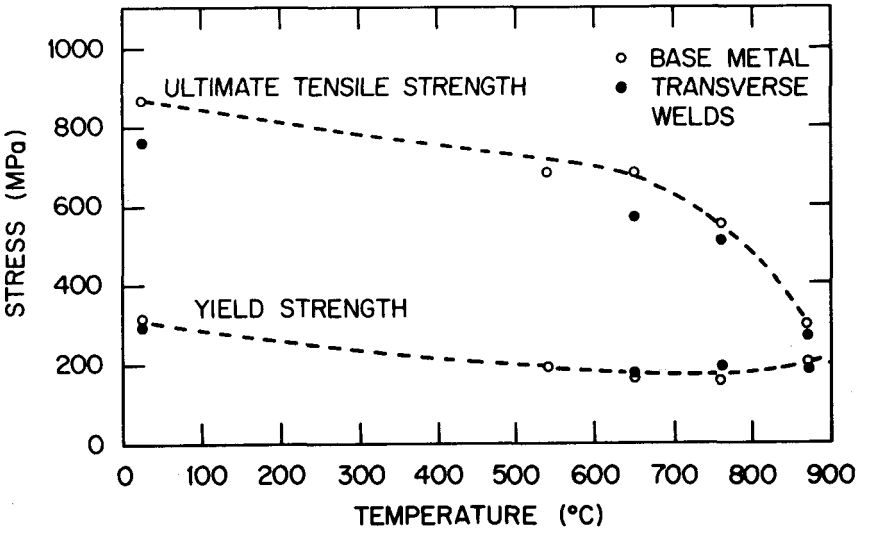

Fig. 3. Tensile properties of modified Inconel 617 alloy 493 annealed 1 h at 1177°C.

three alloys. Transverse weld samples were consistently weaker than base metal, and failure occurred in the weld metal. Aging the annealed base metal samples 12,500 h in HTGR-He appeared to cause a small amount of aging reaction, with the largest amount occurring at the lowest aging temperature of 593°C. The aging response seems to alter only the yield strength for this alloy under these aging conditions. Aging the as-received material for 20,500 h in HTGR-He caused considerable stress relaxation.

The fracture strain of alloy 494 was good for all conditions except the as-received material, which had a large amount of cold work.

The test results from several tensile tests are shown in Table 5. The creep tests were discontinued after a rather long exposure, and the specimens were tensile tested at 25°C. The first three tests involved alloy 492 at test temperatures of 593 and 704°C and test times of 15,000 to 20,000 h. The highest strength resulted from aging at 593°C, but the lowest fracture strain resulted from aging at 704°C. The yield strengths of all three samples were at least double that of the as-annealed material, and the ultimate tensile strength was about 1 1/2 times that of the as-annealed material. Three tests involved discontinued creep

Table 4. Tensile properties of modified Inconel 617 alloy 494

Aging temperature		Test temperature		0.2% Yield strength		Ultimate tensile strength		Elongation (%)		Reduction of area (%)	Specimen type[a]	Failure location[a]
(°C)	(°F)	(°C)	(°F)	(MPa)	(ksi)	(MPa)	(ksi)	Uniform	Total			
						As received						
		25	77	1295	188.0	1373	199.2	2.1	6.4	44.8	B	
		25	77	489	71.0	792	114.9	20.5	22.1	38.3	TW	W
						Annealed 1 h at 1177°C						
		25	77	325	47.2	867	125.8	45.0	49.8	57.5	B	
		538	1000	211	30.6	706	102.4	49.2	51.1	53.7	B	
		649	1200	205	29.8	700	101.6	49.9	51.5	39.2	B	
		760	1400	271	39.3	515	74.8	18.3	50.2	52.9	B	
		871	1600	139	20.2	278	40.3	6.0	74.7	67.3	B	
		25	77	318	46.2	681	98.8	26.8	25.3	36.2	TW	B
		649	1200	200	29.0	547	79.4	28.8	29.9	32.8	TW	W
		760	1400	183	26.6	490	71.1	26.7	34.1	40.8	TW	W
		871	1600	208	30.2	263	38.2	1.7	45.1	63.3	TW	B
						Annealed 1 h at 1177°C, aged 12,500 h in HTGR-He						
593	1100	25	77	397	57.6	834	121.0	47.5	48.9	46.6	B	
704	1300	25	77	378	54.9	864	125.4	45.6	47.3	48.0	B	
871	1600	25	77	290	42.1	777	112.7	51.5	54.7	65.9	B	
						As received, aged 20,500 h in HTGR-He						
593	1100	25	77	749	108.7	1183	171.7	20.8	23.8	51.0	B	
704	1300	25	77	558	81.0	1061	154.0	30.9	34.0	55.0	B	
871	1600	25	77	489	70.9	1008	146.3	37.5	40.8	63.8	B	

[a]B = base metal, TW = transverse weld, W = weld metal.

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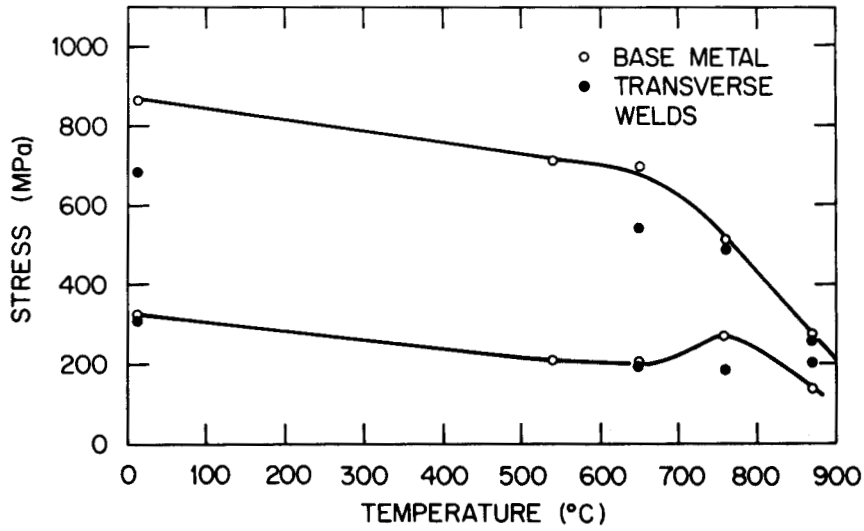

Fig. 4. Tensile properties of modified Inconel 617 alloy 494 annealed 1 h at 1177°C.

tests on alloy 493. The results from the two specimens tested as received are difficult to interpret because those specimens were softer than the as-received material. The one annealed sample tested at 593°C had hardened during the creep test. The sample of alloy 494 weld metal was tensile tested after 15,426 h exposure at 871°C. The yield stress was slightly higher than that of annealed base metal, and the ultimate tensile stress was much lower than that of base metal. The fracture strain was also lower than that of base metal.

Impact Test Results

Several impact specimens of alloys 492, 493, and 494 were sealed in cans and aged in an inert environment. Each alloy was tested as received and after aging 10,000 h at 704 and 871°C; the results are given in Table 6. All three alloys had high impact energies in the as-received condition. Aging at 704°C resulted in the lowest impact energy. Alloy 492 had lower impact energy after aging at 704 and 871°C than did the other two alloys. The lowest value noted was 24 J. (Alloy 492 has the chemical composition closest to that of Inconel 617.)

All three alloys exhibit aging instabilities, but the degree of embrittlement is less as the chromium content of the alloy is decreased.

Table 5. Tensile properties of modified Inconel 617 specimens at 25°C after various discontinued creep tests

Alloy	Pretest exposure conditions	0.2% Yield strength		Ultimate tensile strength		Elongation (%)		Reduction of area (%)
		(MPa)	(ksi)	(MPa)	(ksi)	Uniform	Total	
492 (Base)	Annealed 1 h at 1177°C, creep test 23563, 704°C, 138 MPa, 14,972 h in HTGR-He, 0.8% strain, 0.8% reduction of area	634	92.0	1023	148.4	17.6	17.6	15.7
492 (Base)	Annealed 1 h at 1177°C, aged 12,500 h at 593°C in HTGR-He, creep test 23089 in HTGR-He, 593°C, 414 MPa, 20,830 h, 0.9% strain, 1.9% reduction of area	742	107.6	1082	156.9	24.1	24.1	23.1
492 (Base)	Annealed 1 h at 1177°C, aged 12,500 h at 704°C in HTGR-He, creep test 23086 in HTGR-He, 704°C, 138 MPa, 19,902 h, 1.1% strain, 0.2% reduction of area	634	91.9	978	141.9	13.5	13.5	14.8
493 (Base)	As received, creep test 23600 at 760°C and 103 MPa in helium, 16,767 h, 2.6% strain, 0.6% reduction of area	525	76.2	783	113.5	9.9	9.9	9.8

Table 5. (continued)

Alloy	Pretest exposure conditions	0.2% Yield strength		Ultimate tensile strength		Elongation (%)		Reduction of area (%)
		(MPa)	(ksi)	(MPa)	(ksi)	Uniform	Total	
493 (Base)	As received, creep test 23627 at 760°C and 103 MPa in air, 12,737 h, 4.4% strain, 4.0% reduction of area	716	103.9	1103	160.0	14.3	14.3	16.0
493 (Base)	Annealed 1 h at 1177°C, aged 12,500 h at 593°C in HTGR-He, creep test 23336, 593°C, 345 MPa in HTGR-He, 7971 h, 0.6% strain, 0.2% reduction of area	542	78.6	996	144.4	34.3	34.3	21.4
494 (Weld)	Annealed 1 h at 1177°C, creep test 23609, 871°C, 35 MPa in helium, 4.9% strain, 15,426 h, 2.1% reduction of area	374	54.3	503	73.0	5.9	5.9	6.0

Table 6. Results of impact (Charpy V) tests at 25°C on modified Inconel 617 alloys 492, 493, and 494

Alloy	Condition[a]	Impact energy (J)
492	As received	211
492	Aged 10,000 h at 704°C	24
492	Aged 10,000 h at 871°C	77
493	As received	269
493	Aged 10,000 h at 704°C	82
493	Aged 10,000 h at 871°C	196
494	As received	203
494	Aged 10,000 h at 704°C	192
494	Aged 10,000 h at 871°C	247

[a]All samples aged in an inert environment.

Thus, alloy 492 with 22% chromium has the lowest impact values, and alloy 494 with 12% chromium has the highest.

Creep Test Results

The results of creep tests on alloy 492 are given in Table 7, and the minimum creep rate is shown in Fig. 5. The results shown in Fig. 5 are only for base metal and transverse welds that were annealed 1 h at 1177°C before testing. The data plotted show that the creep rate is not influenced detectably by whether the test environment is air or HTGR-He or by whether the sample material is base metal or base metal with a transverse weld. Tests 23563 and 23086 (Table 7) allow a comparison between as-annealed material and material annealed and aged 12,500 h at 704°C. There is very little difference between the results of the two tests, so aging has little, if any, effect on the creep properties. The tensile properties in Table 2 show that the tensile properties at 25°C were increased by aging at 704°C.

The results of creep tests on alloy 493 are given in Table 8. The minimum creep rates for the samples annealed 1 h at 1177°C before testing are shown in Fig. 6. There do not seem to be detectable effects of test environment or whether the samples are totally base metal or have transverse welds. Results are given in Table 8 for several samples tested

Table 7. Summary of creep tests on modified Inconel 617 alloy 492

(All specimens were pretest annealed 1 h at 1177°C and tested in HTGR-He unless otherwise indicated)

Test	Specimen type[a]	Test temperature		Stress		Time to (h)					Minimum creep rate (%/h)	Elongation (%)		Reduction of area (%)
		(°C)	(°F)	(MPa)	(ksi)	1% creep	2% creep	5% creep	Tertiary creep	Rupture or test		Loading	Creep	
23089[b]	B	593	1100	414	60					20,830[c]	1.7 E-5	1.85	0.86	1.89
21604[d]	TW	649	1200	345	50					565	1.7 E-4	7.8	1.6[e]	16.2
22235	TW	649	1200	345	50	75				476	3.0 E-4	9.3	2.3	16.7
21594	B	649	1200	345	50	2,345	3,750	5,740	2,380	6,196	7.0 E-5	6.5	7.5	14.3
23563	B	704	1300	138	20					14,973[c]	1.9 E-5	0.02	0.8	0.8
23086[b]	B	704	1300	138	20	~20,000				19,902[c]	3.1 E-5		1.07	0.16
22215[f]	TW	760	1400	207	30	1.3	3	10		55.8	2.4 E-1	8.0	18.5[e]	31.7
22947[f]	B	760	1400	207	30	3	6.5	20	41	116	2.2 E-1	0.8	63.3	70.2
22182	TW	760	1400	138	20	15	35	163	1,310	1,482	3.3 E-3	0.06	13.6	17.4
21601	B	760	1400	138	20	25	50	190	1,650	2,293	4.2 E-3		22.5	27.3
22236	B	760	1400	69	10	2,180				18,144[c]	7.4 E-5		1.44	0.3
21614	B	871	1600	103	15	1.5	3	7.5		38	6.5 E-1		41.8	58.0
22176	TW	871	1600	103	15	1	2	7		34	4.0 E-1	0.07	32.0[e]	57.9
23595	TW	871	1600	103	15	8	18	44	169	182	6.6 E-2	0.12	18.2[e]	65.6
23099	B	871	1600	69	10	35	60	135	150	354	3.5 E-2	0.3	28.3	31.0
23885	B	871	1600	48	7	130	320	1,280	4,800	6,139	2.0 E-3	0.2	21.5	24.3
22237	B	871	1600	35	5	460	1,756	7,200	5,200	12,743	3.9 E-4		17.2	
23068	TW	871	1600	35	5	2,250	6,000	13,700	8,000	20,607	2.5 E-4	0.003	24.2[e]	2.8

[a]B = base metal; TW = transverse weld.

[b]Aged 12,500 h in HTGR-He at test temperature.

[c]Discontinued before fracture.

[d]As received.

[e]Failed in weld metal.

[f]Tested in air.

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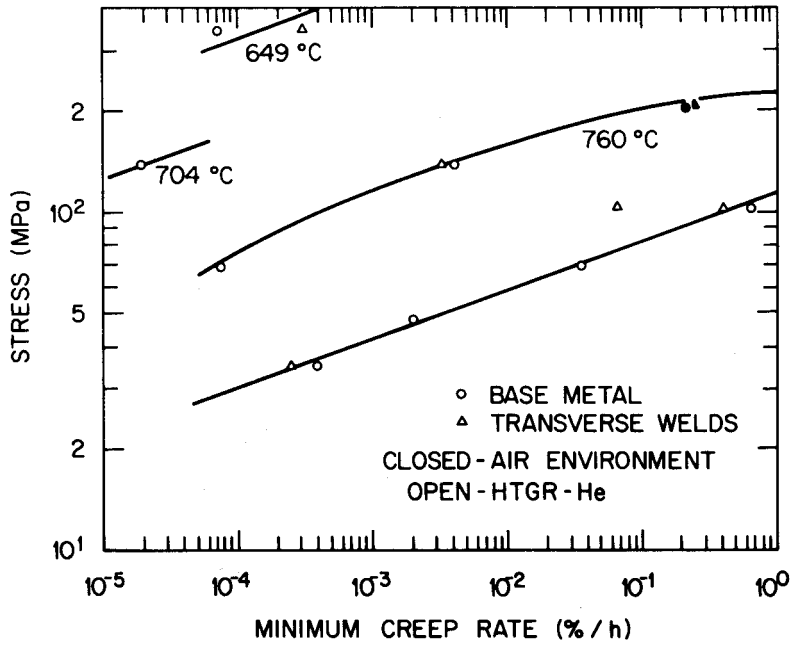

Fig. 5. Minimum creep rate at various stresses for modified Inconel 617 alloy 492. All samples annealed 1 h at 1177°C.

in the as-received condition. The creep characteristics are not significantly different for annealed and as-received material. There is one test on an aged sample, and the creep behavior of the aged and unaged samples are very similar.

The results of creep tests on alloy 494 are given in Table 9, and minimum creep rate data are shown in Fig. 7. The same factors noted for the other two alloys seem to apply to these data also. Pretest annealing, aging, and welding seem to have little, if any, effect on the creep properties.

Even though samples with a transverse weld had about the same creep properties as the base metal, failure consistently occurred in the weld metal. Thus, the weld metal is either slightly weaker or fractures more easily than the base metal.

Carbon Analyses of Tested Samples

Most of the creep specimens tested in HTGR-He were analyzed for carbon. The results of these tests are shown in Fig. 8, and some

Table 8. Summary of creep tests on modified Inconel 617 alloy 493

(All specimens were pretest annealed 1 h at 1177°C and tested in HTGR-He unless otherwise indicated)

Test	Specimen type[a]	Test temperature		Stress		Time to (h)					Minimum creep rate (%/h)	Elongation (%)		Reduction of area (%)
		(°C)	(°F)	(MPa)	(ksi)	1% creep	2% creep	5% creep	Tertiary creep	Rupture or test		Loading	Creep	
23336[b]	B	593	1100	345	50					7,971[c]	2.1 E-5	0.34	0.55	0.16
22187	TW	649	1200	345	50	18	57	157	1,050	1,133	7.3 E-3	8.8	16.1[d]	31.5
21589	B	649	1200	345	50	90	150	410	2,000	2,408	3.2 E-3	8.0	15.8	18.7
23096	B	704	1300	138	20	550	1,500	3,850		3,700	3.5 E-3	0.2	32.7	65.4
23363	B	704	1300	138	20	550	1,500	3,850		4,201[c]	1.1 E-3		5.4	5.2
23839[b]	B	704	1300	138	20	210	525	1,800	6,700	7,901	1.9 E-3	0.01	22.4	20.9
21608[e]	TW	760	1400	138	20	12	33	100	425	724	3.9 E-2		46.1[d]	57.7
21605	B	760	1400	138	20	42	75	185	680	1,007	2.7 E-2	0.03	51.3	60.6
23627[e,f]	B	760	1400	103	15	65	430	11,583	930	12,737[c]	1.8 E-4		4.4	4.0
23600[e]	B	760	1400	103	15	11,200				16,767[c]	4.4 E-5		2.6	0.6
22216[f]	TW	760	1400	103	15	97	160	525	1,290	2,847	9.0 E-3	0.14	41.7[d]	30.4
24319	B	760	1400	69	10	700	1,880			3,093[g]	8.4 E-4		3.0	
21615	B	871	1600	103	15	3.5	7	17	60	115	3.3 E-1		79.3	74.5
22178	TW	871	1600	103	15	1.5	2.5	7	13	29	7.3 E-1	0.09	31.6[d]	35.3
23857[e]	TW	871	1600	69	10	16	20	74	176	200	5.6 E-2	0.28	17.1[d]	19.8
23648	TW	871	1600	35	5	630	1,040	2,070	850	3,904	1.7 E-3	0.12	16.4[d]	10.0
22769	B	871	1600	35	5	180	430	910	650	2,022	4.3 E-3	0.03	21.9	23.9

[a]B = base metal; TW = transverse weld.

[b]Aged 12,500 h in HTGR-He at test temperature.

[c]Discontinued before fracture.

[d]Failed in weld metal.

[e]As received.

[f]Tested in air.

[g]Test still in progress.

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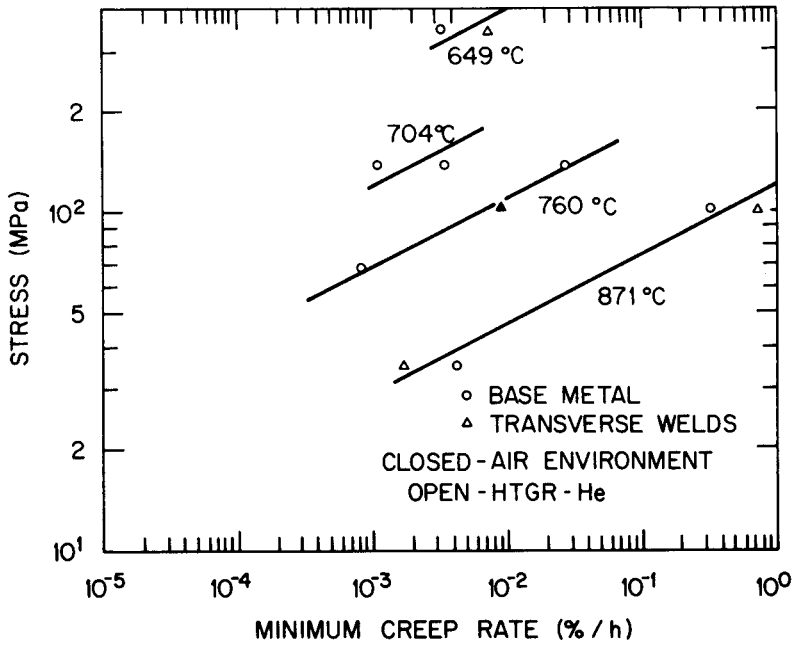

Fig. 6. Minimum creep rate at various stresses for modified Inconel 617 alloy 493. All samples annealed 1 h at 1177°C.

statistical comparisons are presented in Table 10. The analytical samples were taken so that they included the entire specimen cross section. Thus, the values shown in Fig. 8 are averages of the cross sections. The most important observation is that none of the carbon concentrations are very high. In the statistical exercise summarized in Table 10, all of the data from one alloy were considered as a set, and exposure temperature was not considered as a variable. There is very little evidence of carburization, and some samples even indicate a small amount of decarburization.

Metallographic Studies

Typical photomicrographs of alloys 492, 493, and 494 are shown in Figs. 9 through 11, respectively. Alloys 492 and 493 are rather large grained and have occasional stringers and precipitate particles. Alloy 494 (Fig. 11) has a finer grain size, and the stringers are more pronounced. It is not known whether the presence or absence of stringers is a sampling problem or whether stringers exist in some alloys and not in others.

Table 9. Summary of creep tests on modified Inconel 617 alloy 494

(All specimens were pretest annealed 1 h at 1177°C and tested in HTGR-He unless otherwise indicated)

Test	Specimen type[a]	Test temperature		Stress		Time to (h)					Minimum creep rate (%/h)	Elongation (%)		Reduction of area (%)
		(°C)	(°F)	(MPa)	(ksi)	1% creep	2% creep	5% creep	Tertiary creep	Rupture or test		Loading	Creep	
21599[b]	B	649	1200	345	50	32	72	195	500	714	2.3 E-2	5.3	32.8	46.1
22192	TW	649	1200	345	50	10	31	92	175	253	4.5 E-2	8.8	16.5[c]	34.0
23840[b]	B	704	1300	138	20	195	525	1,558	3,300	6,266	3.0 E-3	0.04	34.3	30.4
23622[d]	B	704	1300	138	20	310	740	2,080	2,800	5,499	2.2 E-3		24.6	23.3
21609	B	760	1400	138	20	35	75	185	700	1,006	2.6 E-2	0.03	40.2	48.2
21613	TW	760	1400	138	20	15	35	98	250	315	5.0 E-1	0.01	20.9[c]	34.3
23847	B	760	1400	103	15	21	100	450	1,800	3,083	6.1 E-3		36.5	38.2
22217	TW	760	1400	103	15	81	170	512	1,300	1,553	8.5 E-3		19.4	20.4
22191	TW	871	1600	103	15	1	2	6	20	28	8.3 E-1		31.9[c]	53.9
22177	B	871	1600	103	15	1.5	3	7	21	37	7.0 E-1		41.0	56.0
23601	B	871	1600	69	10	12	24	220	125	232	8.2 E-2		40.1	40.2
22768	B	871	1600	35	5	490	980	2,310	2,250	2,872	2.0 E-3	0.05	11.1	18.9
23610[b]	TW	871	1600	35	5	630	790		475	946	3.5 E-4	0.13	5.3[c]	3.5
23609[b]	W	871	1600	35	5	3,600				15,426[e]	6.3 E-5		4.9	8.0

[a]B = base metal; TW = transverse weld; W = 100% weld deposit.

[b]As received.

[c]Failed in weld metal.

[d]Aged 12,500 h in HTGR-He at test temperature.

[e]Discontinued before fracture.

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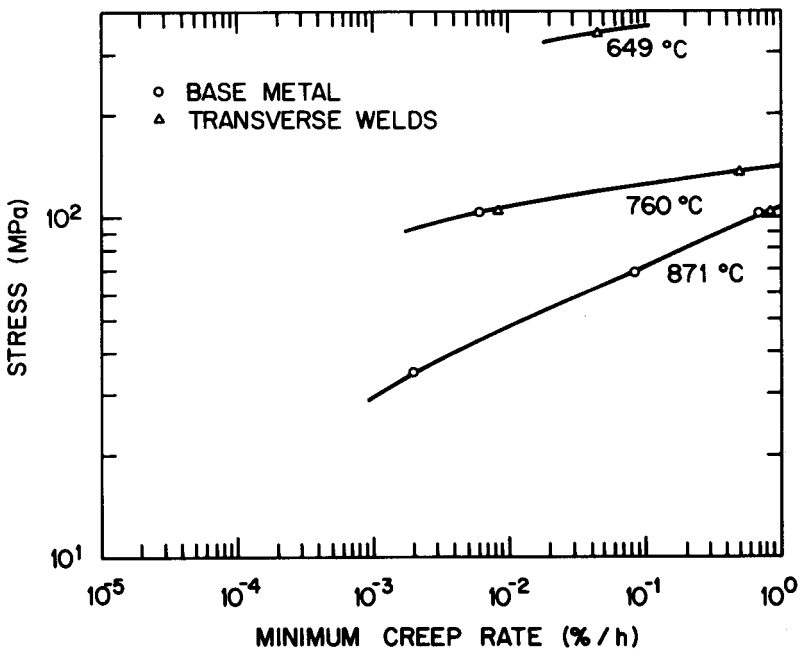

Fig. 7. Minimum creep rate at various stresses for modified Inconel 617 alloy 494. All samples annealed 1 h at 1177°C.

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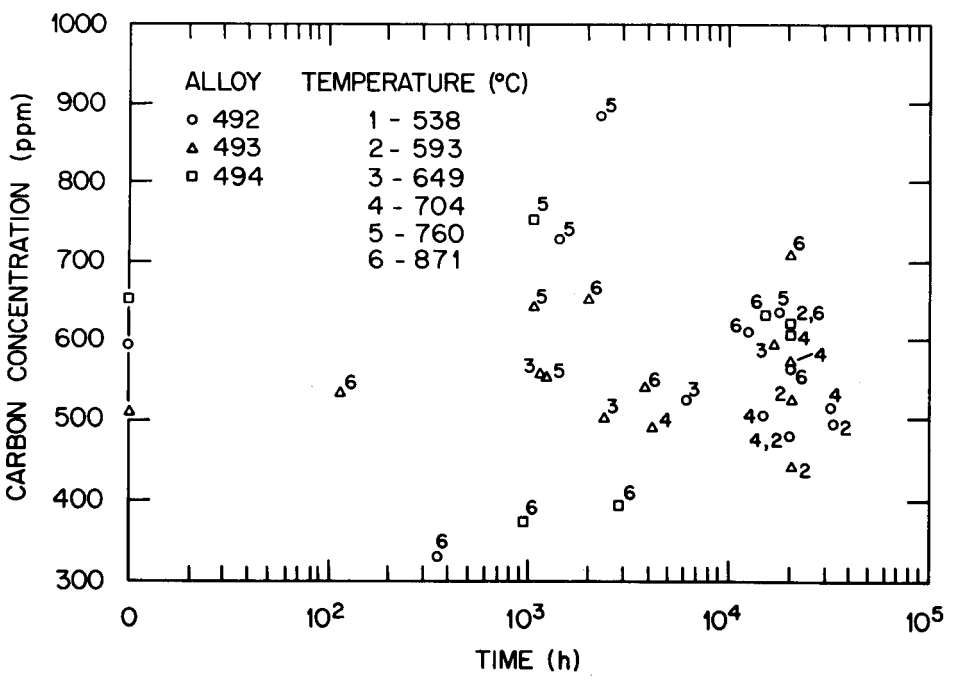


Fig. 8. Average carbon concentrations of several modified Inconel 617 alloys after creep testing.

Table 10. Statistical evaluation of carbon data for creep test samples of modified Inconel 617 alloys

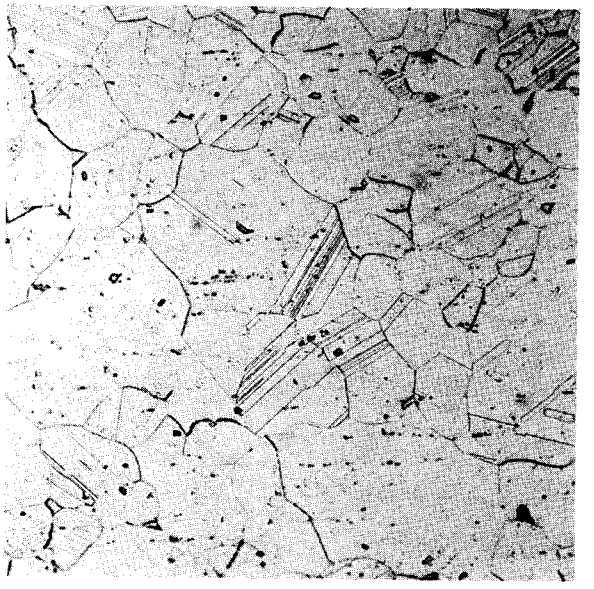
Alloy	Number of observations	Average (ppm)	Standard deviation (ppm)
492	12	563	141
493	13	563	71
494	8	584	130

Typical oxides that formed on several of the alloys are shown in Fig. 12. There is some tendency toward internal oxidation, but the depth of oxidation is shallow for the times and temperatures involved.

Several samples of alloys 492, 493, and 494 were annealed 1 h at 1177°C and then aged 12,500 h at various temperatures. Photomicrographs after agings at 704 and 871°C are shown in Figs. 13 through 18. (Recall from Tables 2 through 4 that aging at 704°C caused considerable hardening and that aging at 871°C resulted in material with about the same strength as that having had only the 1-h anneal at 1177°C.) Figures 13 and 14 show that aging at 704 and 871°C caused considerable precipitation (compare with Fig. 9). The precipitate morphologies after aging at 704 and 871°C differ from each other, but it is difficult to predict the one having the highest strength on the basis of Figs. 13 and 14. Alloy 493 did not form extensive coarse precipitate after aging at 704 or 871°C (Figs. 15 and 16). The etching characteristics of these samples indicated that the precipitate was very fine. Aging alloy 493 at 704°C (Fig. 17) led to some rearrangement of the precipitate, and aging at 871°C (Fig. 18) appeared to dissolve the precipitate.

Several samples were examined after various creep exposures. The microstructure of a sample of alloy 492 creep tested at 760°C for 18,144 h is shown in Fig. 19. This sample was not tensile tested after exposure, but samples aged at 704°C (Table 2) were strengthened. It is likely that the microstructure of fine precipitate in Fig. 19 would be quite strong. Testing at 871°C resulted in considerably coarser precipitate (Fig. 20),

Y203275



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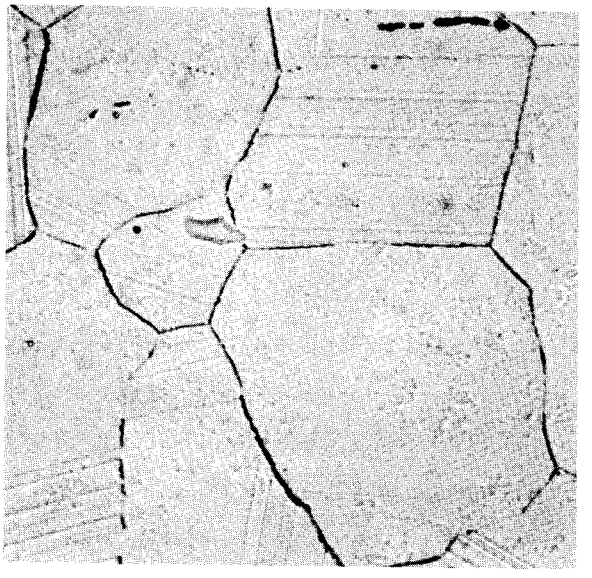
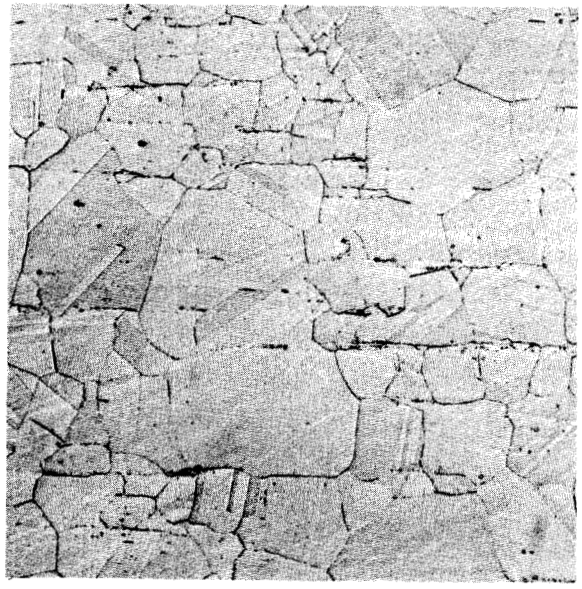
Y203276



40 μm

Fig. 9. Typical specimens of modified Inconel 617 alloy 492 annealed 1 h at 1177°C.

Y203253



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Y203250

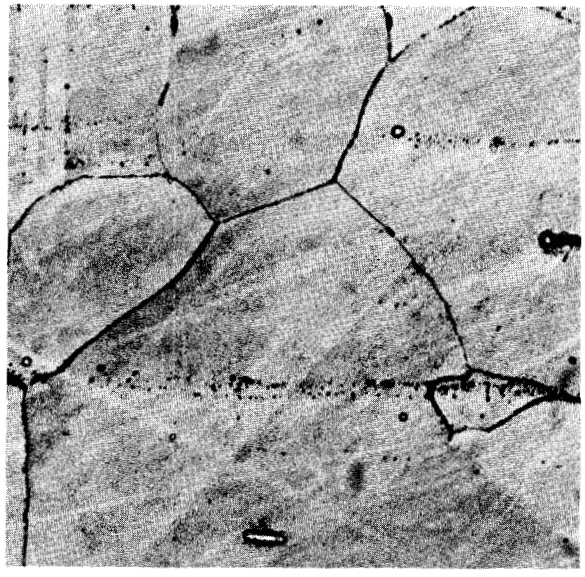

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Fig. 10. Typical specimens of modified Inconel 617 alloy 493 annealed 1 h at 1177°C.

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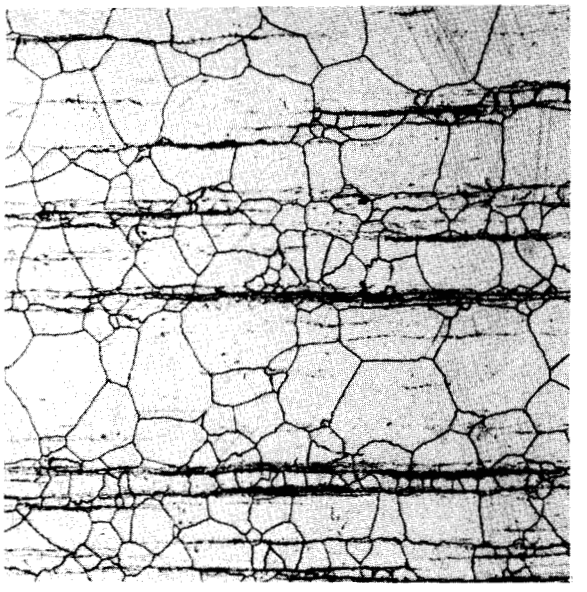

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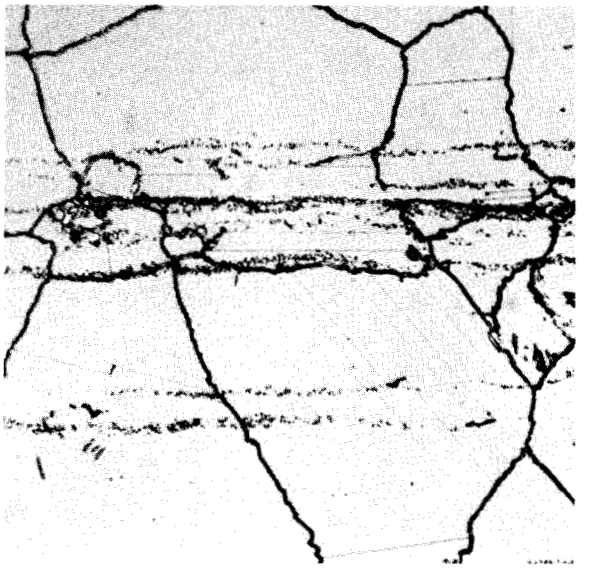

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Fig. 11. Typical specimens of modified Inconel 617 alloy 494 annealed 1 h at 1177°C.

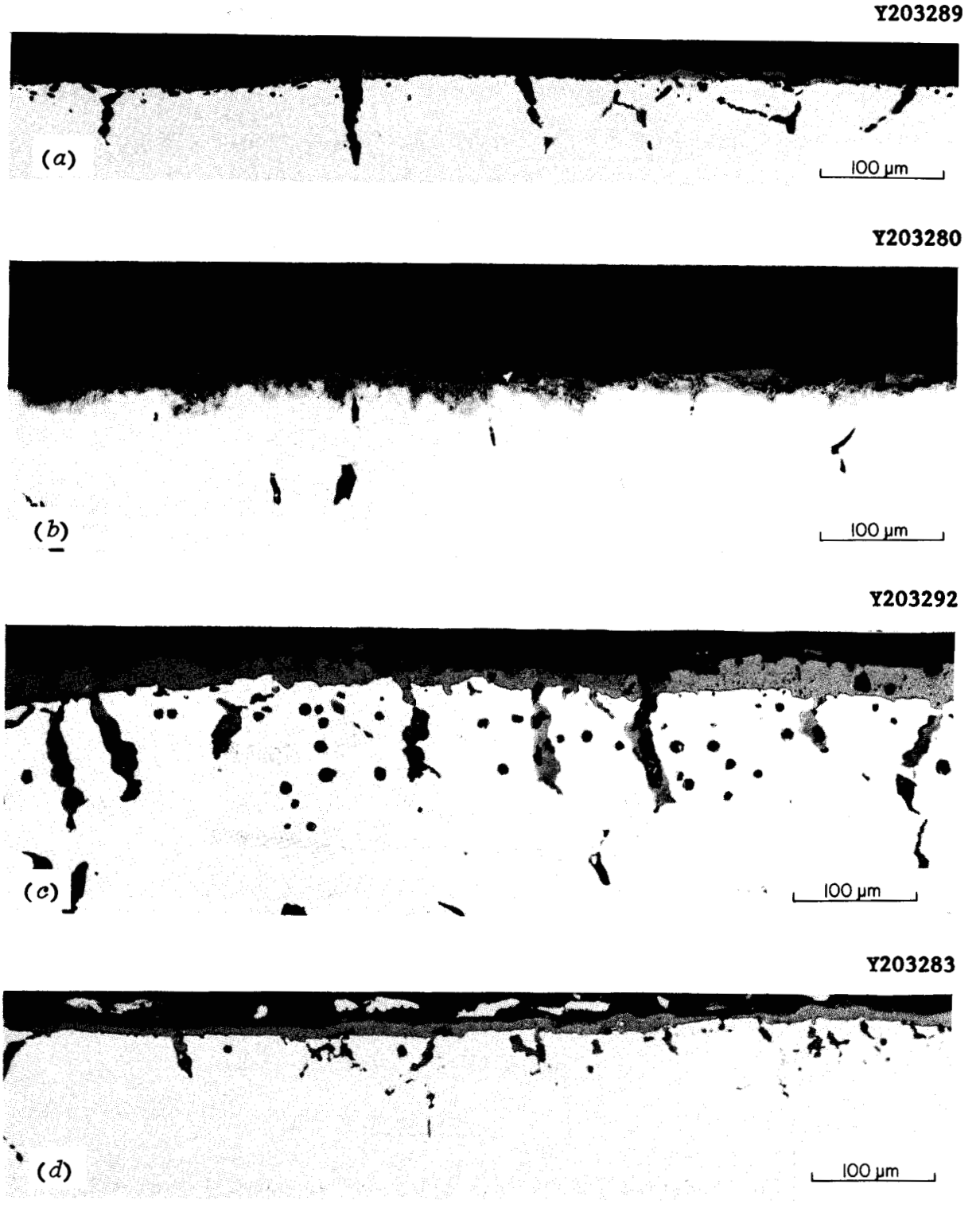
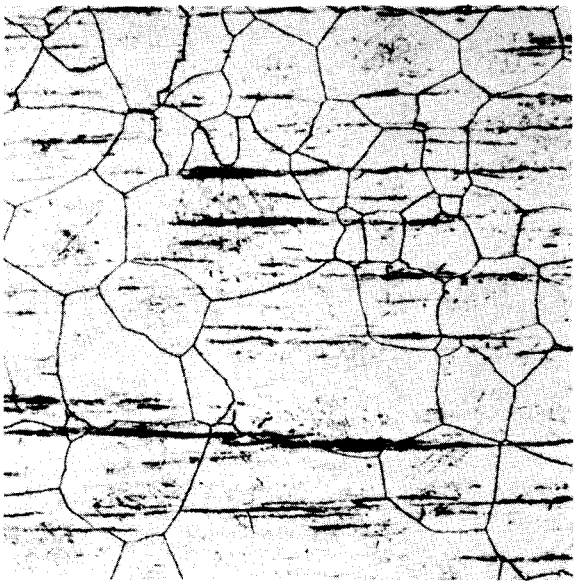


Fig. 12. As-polished edges of tested specimens of modified Inconel 617. The oxide formation during each test is visible on the edge of the polished specimen. (*a*) Alloy 492, 18,144 h at 760°C. (*b*) Alloy 494, 3083 h at 760°C. (*c*) Alloy 492, 12,743 h at 871°C. (*d*) Alloy 494, 2872 h at 871°C.

Y203293



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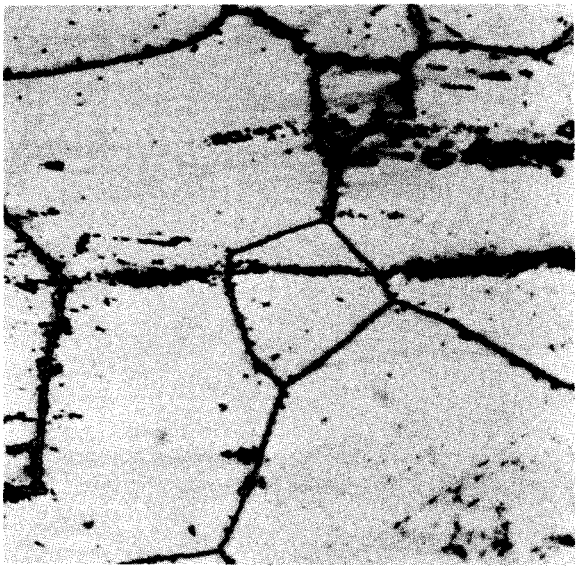

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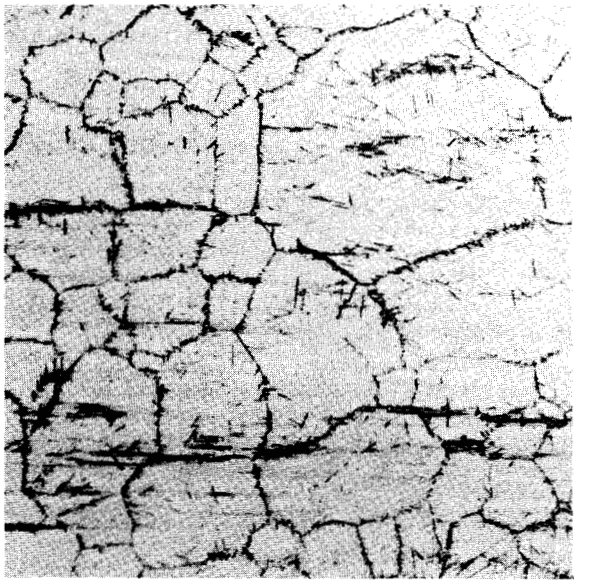
Fig. 13. Modified Inconel 617 alloy 492 annealed 1 h at 492°C and aged 12,500 h at 704°C in HTGR-He.

Y203295



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Y203296

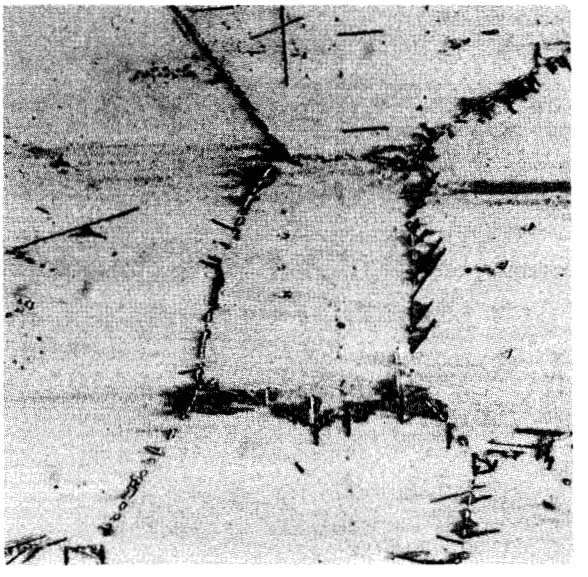

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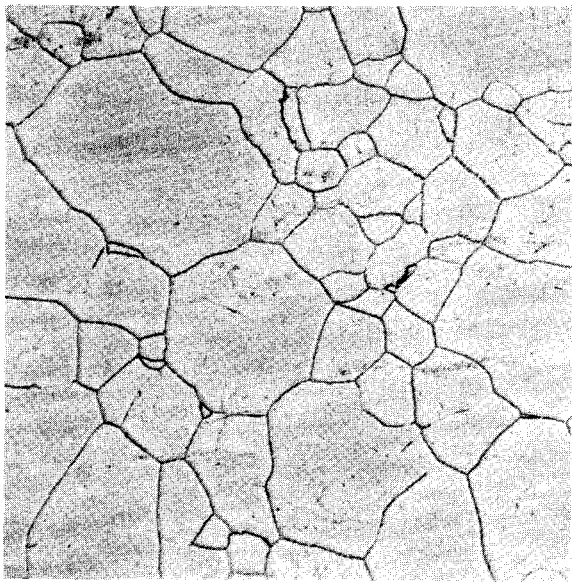
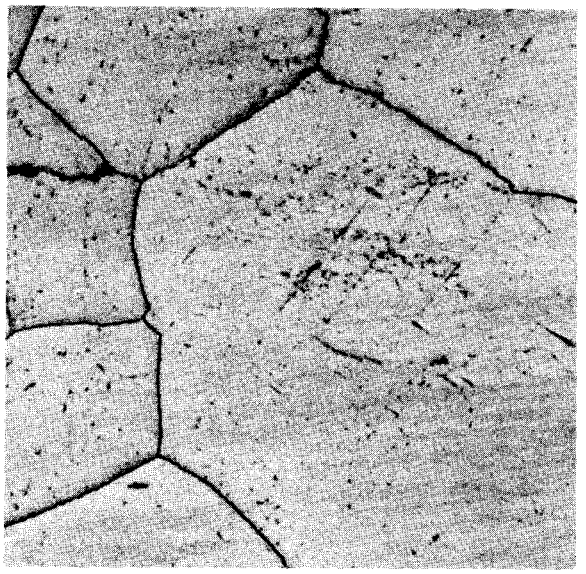
Fig. 14. Modified Inconel 617 alloy 492 annealed 1 h at 492°C and aged 12,500 h at 871°C in HTGR-He.

Y203297



200 μm

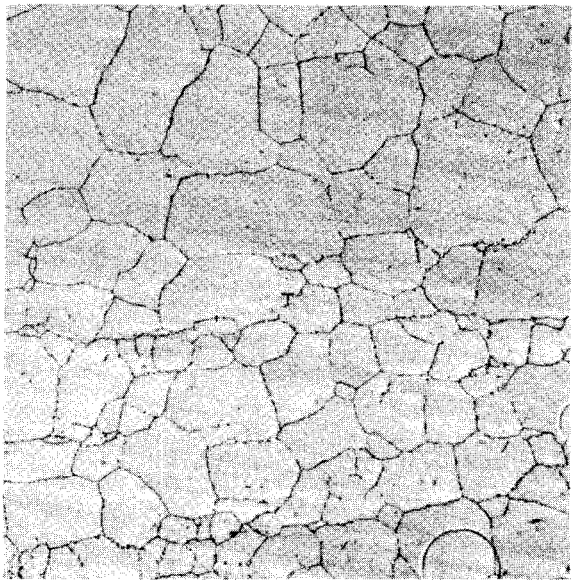
Y203298



40 μm

Fig. 15. Modified Inconel 617 alloy 493 annealed 1 h at 1177°C and aged 12,500 h at 704°C in HTGR-He.

Y203299



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Y203300

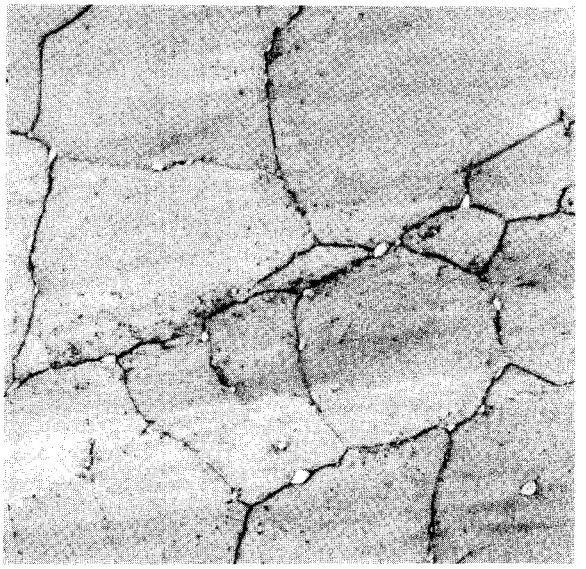

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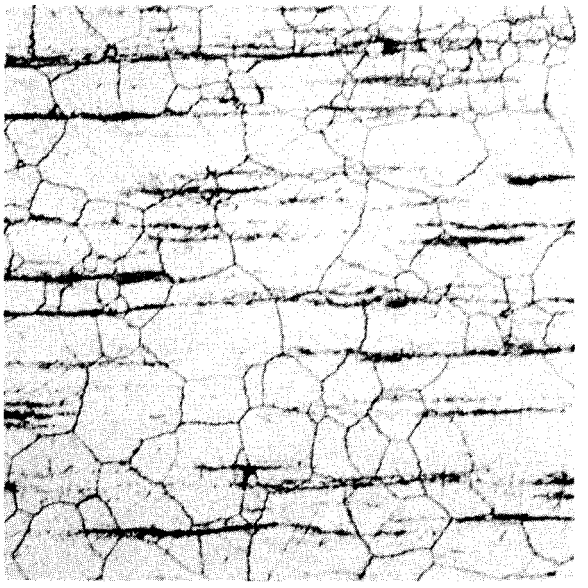
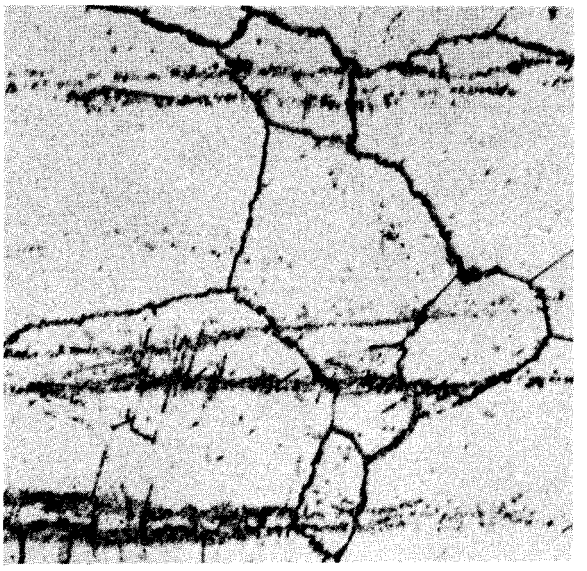
Fig. 16. Modified Inconel 617 alloy 493 annealed 1 h at 1177°C and aged 12,500 h at 871°C in HTGR-He.

Y203301



200 μm

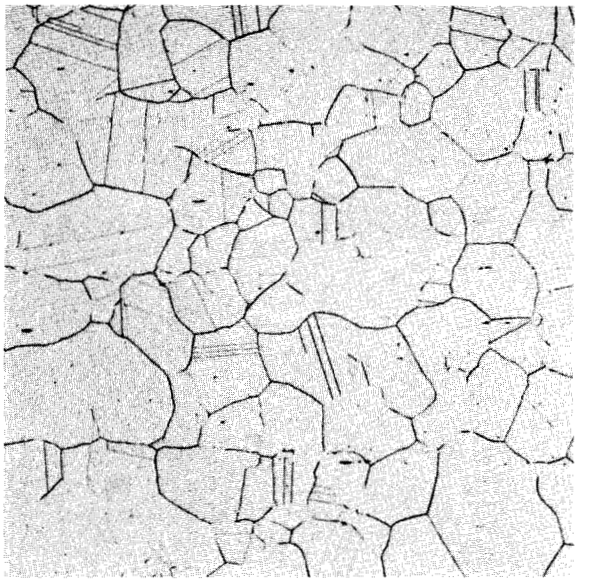
Y203302



40 μm

Fig. 17. Modified Inconel 617 alloy 494 annealed 1 h at 1177°C and aged 12,500 h at 704°C in HTGR-He.

Y203303



200 μm

Y203304

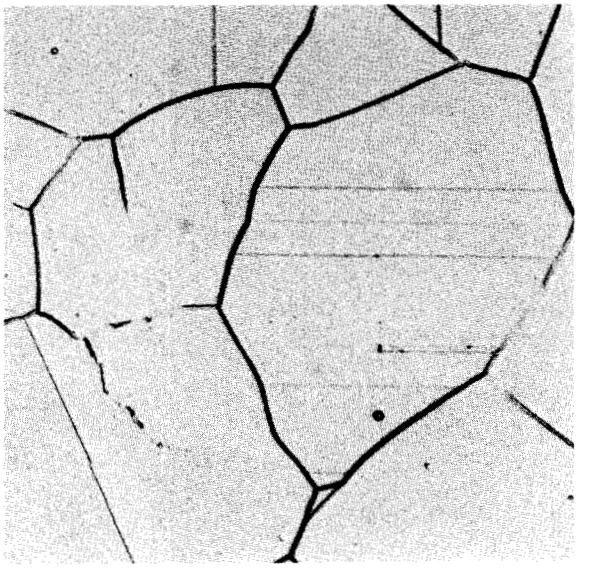


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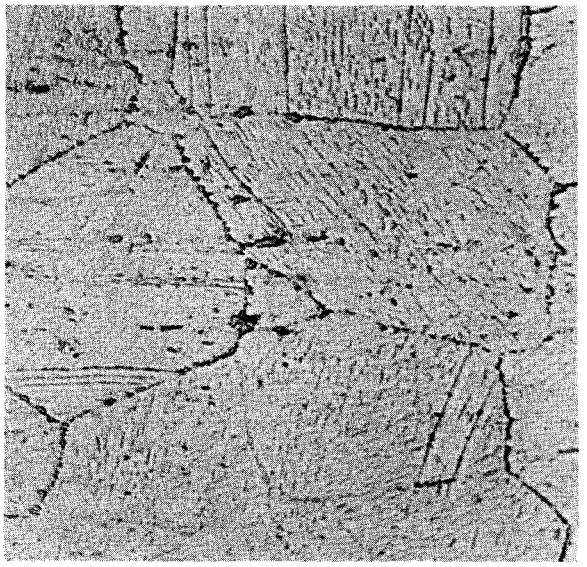
Fig. 18. Modified Inconel 617 alloy 494 annealed 1 h at 1177°C and aged 12,500 h at 871°C in HTGR-He.

Y203287

200 μm

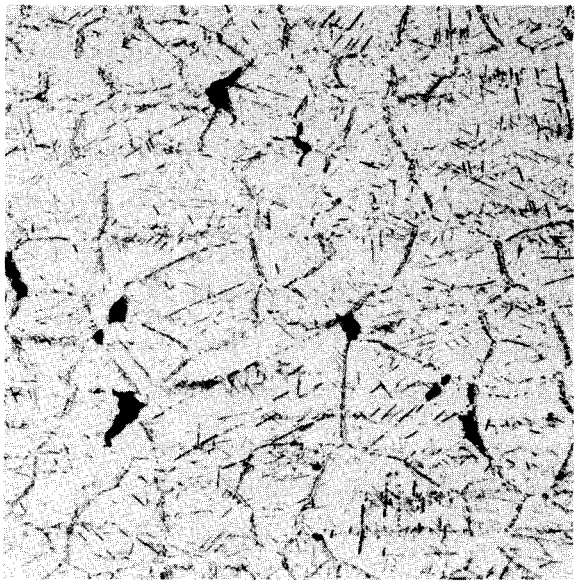
Y203288



40 μm

Fig. 19. Modified Inconel 617 alloy 492 after exposure to HTGR-He in creep test 22236. Annealed 1 h at 1177°C and stressed 18,144 h at 760°C before testing was discontinued.

Y203290



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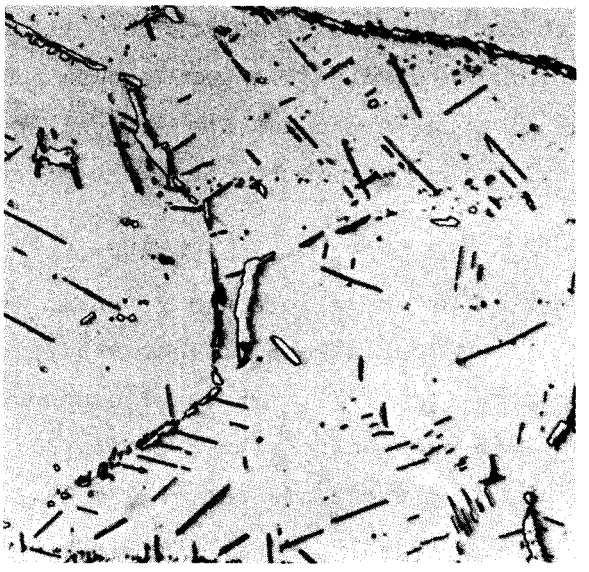
Y203291



40 μm

Fig. 20. Modified Inconel 617 alloy 492 after creep test 22237. Annealed 1 h at 1177°C and exposed 12,743 h at 871°C before rupture. (Photomicrograph ~6 mm from fracture.)

and the strength was not increased (Table 2). The microstructure of alloy 493 after testing at 871°C is shown in Fig. 21. As discussed relative to Fig. 16, the etching characteristics of this alloy aged at 871°C indicate that a very fine precipitate is present; however, this was not confirmed. Photomicrographs of a sample of alloy 494 after testing at 760°C for 3083 h are shown in Fig. 22, and photomicrographs of a sample after testing 2872 h at 871°C are shown in Fig. 23. The precipitate in Figs. 22 and 23 is redistributed slightly from that of the as-received material (Fig. 11). However, the stringers in the as-annealed material seem largely intact.

MODIFIED INCONEL 617 ALLOYS 800 THROUGH 805

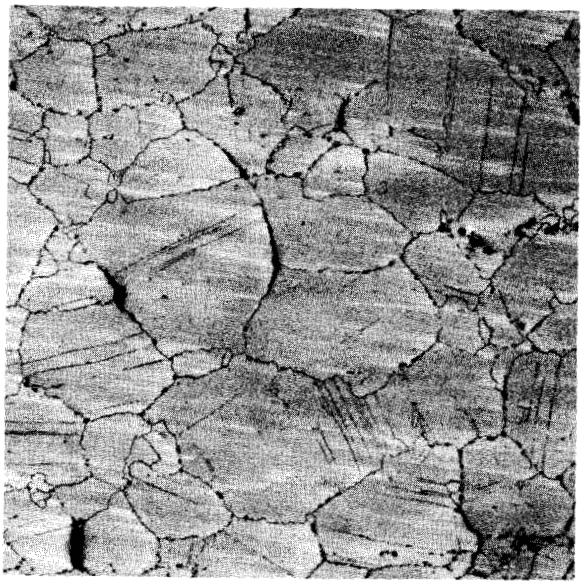
Source

The alloys in this series were made in our facility at ORNL. The melts were each a few kilograms. They were arc melted on a water-cooled hearth from virgin stock and drop cast into an ingot about 2.5 cm (1 in.) in diam by 15 cm (6 in.) long. The ingots were hot worked at 871°C down to 0.95 cm (0.375 in.) in diam. This gave enough material to make six to eight specimens of each material. The nominal compositions are given in Table 1, along with the ORNL carbon analyses of 860 to 917 ppm.

Tensile Test Results

Tensile properties of the alloys are given in Table 11 at three temperatures. The first four alloys reflect variations in aluminum and titanium concentrations (Table 1). These elements would result in hardening if the alloys were heated for a sufficient time before testing, but it is likely that only the tests run at 871°C would have been at temperature sufficiently long to cause hardening. Alloy 801 contained 2% titanium and 0.5% aluminum and was the strongest of the alloys at 871°C. At test temperatures of 25 and 649°C, the strengths of alloys 800, 801, 802, and 804 were about the same. The last three alloys — 803, 804, and 805 — reflect the effects of reducing the chromium level. The variations in strength among these alloys is within 15% and a bit erratic. The yield and ultimate tensile strengths at a test temperature of 25°C,

Y203285



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Y203286

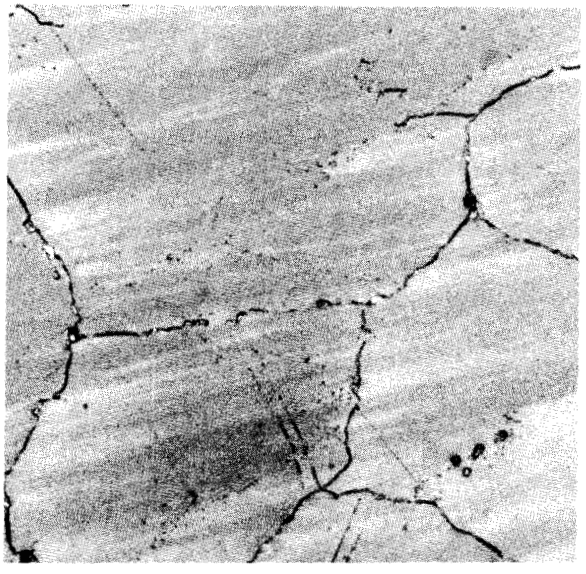

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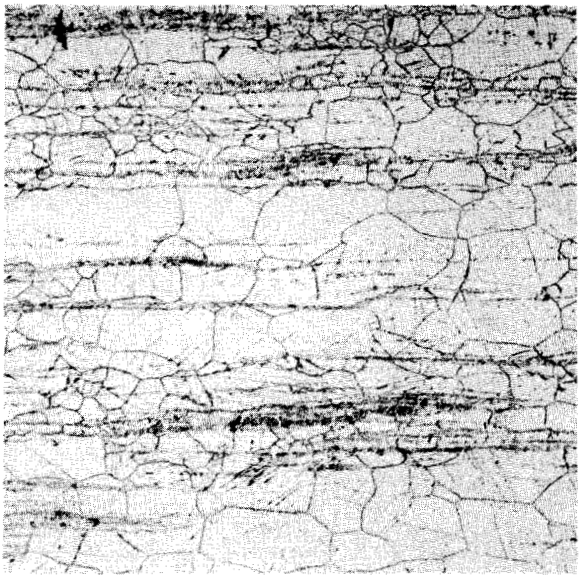
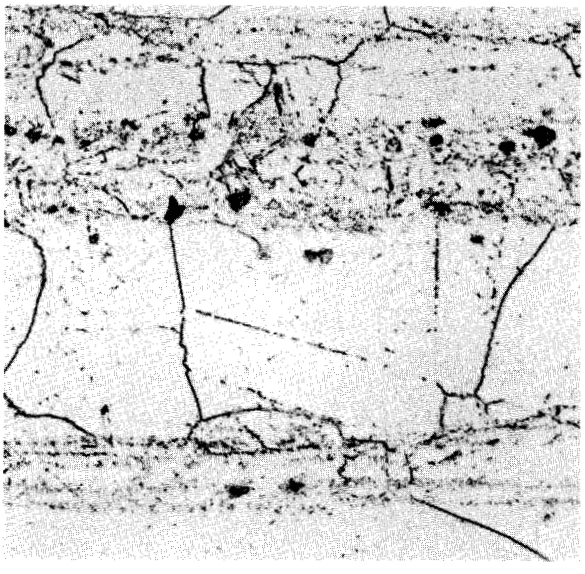
Fig. 21. Modified Inconel 617 alloy 493 after creep test 22769. Annealed 1 h at 1177°C and exposed 2022 h at 871°C before rupture. (Photomicrograph ~6 mm from fracture.)

Y203279



200 μm

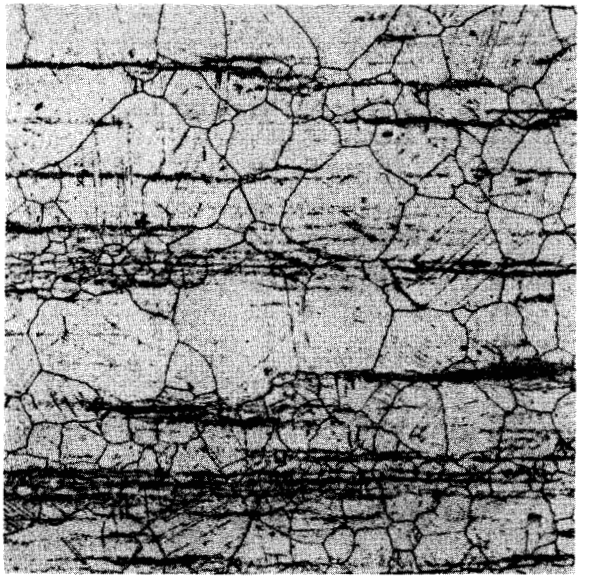
Y203281



40 μm

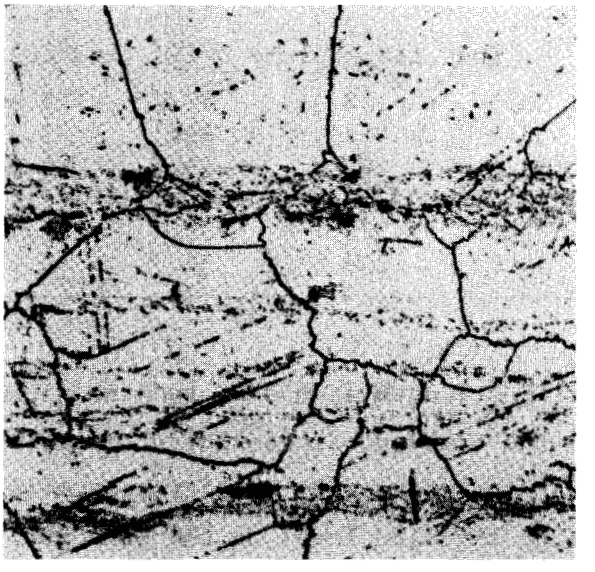
Fig. 22. Modified Inconel 617 alloy 494 after creep test 23847. Annealed 1 h at 1177°C and exposed 3083 h at 760°C before rupture. (Photomicrograph ~6 mm from fracture.)

Y203282



200 μm

Y203284



40 μm

Fig. 23. Modified Inconel 617 alloy 494 after creep test 22768. Annealed 1 h at 1177°C and exposed 2872 h at 871°C before rupture. (Photomicrograph ~6 mm from fracture.)

Table 11. Tensile properties of modified Inconel 617 alloys after annealing 1 h at 1177°C

Alloy	0.2% Yield strength		Ultimate tensile strength		Elongation (%)		Reduction of area (%)
	(MPa)	(ksi)	(MPa)	(ksi)	Uniform	Total	
Test temperature 25°C (77°F)							
800	361	52.3	898	130.3	51.5	56.7	56.6
801	381	55.3	900	130.6	50.7	55.4	58.0
802	354	51.4	876	127.1	50.8	54.5	60.1
803	351	50.9	1038	150.5	41.6	45.8	59.2
804	323	46.8	856	124.2	51.4	56.2	59.9
805	315	45.7	847	122.9	49.8	54.6	61.5
Test temperature 650°C (1202°F)							
800	239	34.5	780	113.1	47.7	48.6	40.0
801	255	37.0	736	106.7	49.5	50.8	41.0
802	212	30.8	667	96.7	57.7	59.7	46.3
803	219	31.7	686	99.5	53.9	55.4	41.3
804	208	30.2	647	93.9	49.1	50.4	40.0
805	230	33.4	616	89.3	36.4	37.2	32.3
Test temperature 871°C (1600°F)							
800	265	38.5	288	41.7	9.3	59.1	68.4
801	368	53.4	412	59.7	3.3	32.3	39.5
802	225	32.6	297	43.1	10.0	73.0	57.0
803	223	32.4	279	40.4	7.7	57.7	49.9
804	219	31.6	274	39.7	8.7	60.3	50.5
805	225	32.6	268	38.9	9.0	53.3	43.9

the ultimate tensile strength at 650°C, and the ultimate tensile strength at 871°C all show the trend of decreasing strength with decreasing chromium level. At the other test conditions not mentioned, there is no evident effect of chromium level on the strength.

Creep Test Results

Four creep tests were run on each alloy, and the results are given in Table 12. Two test temperatures were used, and the creep rate results are shown in Fig. 24. At 760°C the creep rate at a given stress level spans about two orders of magnitude. Alloys 800 and 801 are the strongest alloys. These alloys each contain 2% titanium (Table 1) and probably

Table 12. Summary of creep tests on several modified Inconel 617 type alloys

(Tested after anneal of 1 h at 1177°C in air; tested in HTGR-He unless otherwise specified)

Test	Test temperature		Stress		Time to (h)					Minimum creep rate (%/h)	Elongation (%)		Reduction of area (%)
	(°C)	(°F)	(MPa)	(ksi)	1% creep	2% creep	5% creep	Tertiary creep	Rupture		Loading	Creep	
							Alloy 801						
22611[a]	760	1400	206	30	13	37	150		290	2.5 E-3	0.15	11.2	15.9
22211	760	1400	137	20	620	1,430	3,550	4,150	5,394	1.4 E-3		10.8	18.9
22207	871	1600	69	10	7	20	60	220	309	5.2 E-2		24.6	31.5
23090	871	1600	35	5	65	1,005	3,250	2,300	6,916	5.0 E-4	0.04	29.2	30.3
							Alloy 802						
22219[a]	760	1400	206	30	435	620	888	425	956	1.6 E-3	0.17	6.9	7.9
22214	760	1400	137	20	3,950	4,925	5,712	2,550	5,714	7.5 E-5		5.4	6.1
22208	871	1600	69	10	200	358	615	310	770	4.5 E-3	0.04	8.5	14.8
23094	871	1600	35	5	3,400	4,600	6,430	3,000	8,790	1.9 E-4	0.05	20.1	20.0
							Alloy 803						
22229[a]	760	1400	206	30	2.9	4.6	10.5	31	56	4.1 E-1		36.6	36.5
22218	760	1400	137	20	2.3	46	152	213	488	3.1 E-2	0.16	29.6	32.5
22222	871	1600	69	10	540	1,280	3,440	5,000	12,520	1.4 E-3		38.6	32.4
23082	871	1600	35	5	850	1,300	2,470	2,300	7,107	2.2 E-3		37.7	33.7
							Alloy 803						
22712[a]	760	1400	206	30	4	12	44	87	116	1.0 E-1		19.3	21.9
22220	760	1400	138	20	25	57	157	330	593	3.0 E-3	0.06	29.3	33.7
22224	871	1600	69	10	5	13	36	120	195	1.2 E-1		37.1	39.5
							Alloy 804						
22711[a]	760	1400	206	30	3	5	14	39	62.5	3.8 E-1	0.41	39.4	43.0
22221	760	1400	138	20	20	52	124	125	514	3.8 E-2	0.14	44.5	48.2
22226	871	1600	69	10	10	22	55	130	203	8.8 E-2		31.0	34.1
23095	871	1600	35	5	300	750	1,900	2,000	4,758	2.3 E-3	0.08	25.4	23.4
							Alloy 805						
22675[a]	760	1400	206	30	3.5	7.5	20		81	2.2 E-1	0.33	36.8	41.7
22223	760	1400	138	20	25	51	155	318	703	2.8 E-2	0.28	32.1	42.4
22228	871	1600	69	10	15	25	77	206	290	4.5 E-2		22.1	49.6

[a]Tested in air.

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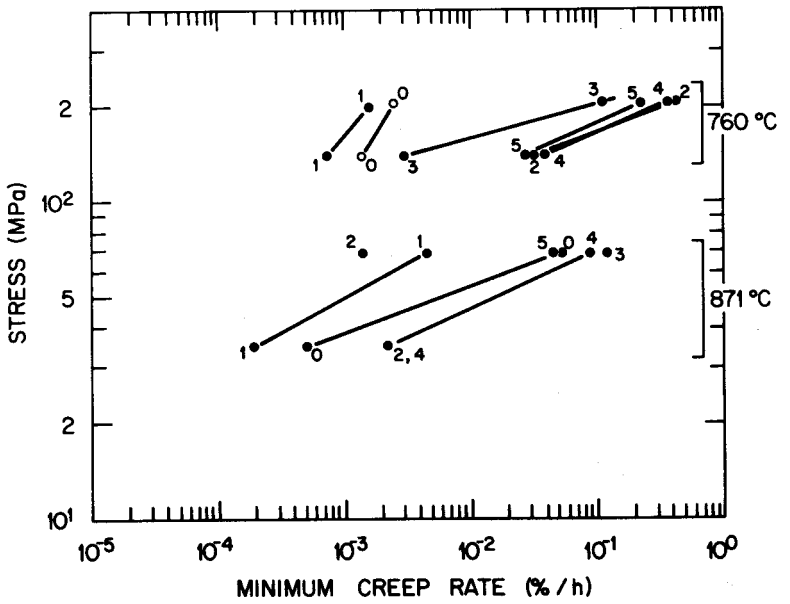


Fig. 24. Creep behavior of modified Inconel 617 alloys in the annealed condition. The numbers 0 through 5 represent the alloys 800 through 805.

enough aluminum to form gamma prime. Alloys 802, 804, and 805 are the weakest and have about equivalent strengths. Alloy 803 falls intermediate, with good strength at a low stress and poor strength at a higher stress. The effect of the chromium variation from 12 to 22% seems to be much less than the concentrations of aluminum and titanium, which control the amount of gamma prime. At a test temperature of 871°C, the creep rates for the six alloys vary by 1 to 1 1/2 orders of magnitude at a given stress level. Alloy 802 is the strongest and would contain the most gamma prime. The other alloys have about equivalent strengths. (The result of the high-stress test on alloy 802 at 871°C appears to be in error.)

Carbon Analyses of Tested Samples

Several of the tested samples were analyzed to determine the extent of carburization. The data are very few, so it is difficult to draw conclusions. On the basis of the data available, alloys 800, 801, and 802 carburized, and alloys 803 and 804 did not carburize. There were no data for alloy 805.

Metallographic Studies

The microstructure of a sample of alloy 801 after creep testing at 760°C is shown in Fig. 25. This was the strongest of the alloys, and the precipitate particles are likely carbides and gamma prime. The sample fractured in 5714 h after 5.4% strain. The microstructure of an alloy-803 sample is shown in Fig. 26 after testing at 760°C. This alloy contains 1% aluminum (compared with 2% for alloy 802) and ran for only 593 h. The precipitates are likely predominantly carbides with little, if any, gamma prime. The microstructures of alloys 804 and 805 after testing at 760°C are shown in Figs. 27 and 28, respectively. These alloys contain 16 and 12% chromium, respectively. The microstructures contain numerous fine precipitates, likely carbides.

IN-519

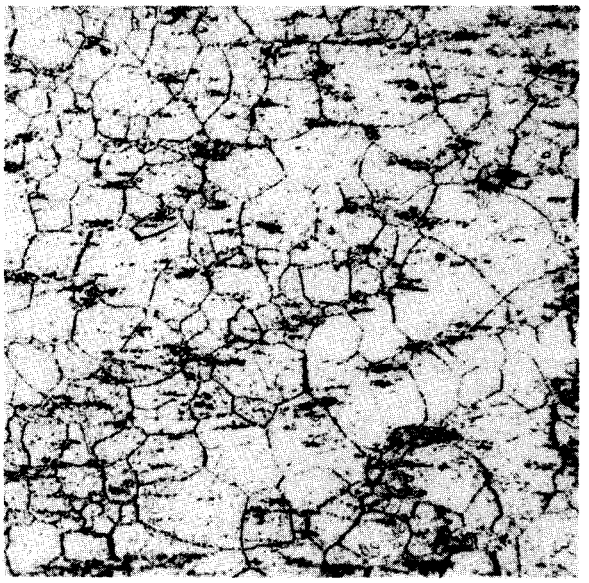
Source

Many of the properties and uses of IN-519 are given in ref. 2. This alloy was developed primarily for centrifugally cast catalyst tubes used for steam-hydrocarbon reforming furnaces. The alloy contains about 1.5% niobium and has excellent resistance to carburization. We did not have the funds to buy the minimum quantity of IN-519 for evaluation, so we obtained statically cast material from Certified Alloy Products, Inc., of Long Beach, California. The mold was fabricated with feeder tubes to cast several short rods 1.3 cm (0.5 in.) in diameter for making specimens. Material of two compositions was obtained. Alloy 2356 contained about 1.5% niobium plus tantalum, and alloy 2357 contained 1.8% titanium and <0.1% niobium plus tantalum. Test bars cast in this way would have a different microstructure than centrifugally cast material, but the chemical characteristics should be similar.

Tensile Test Results

The results of tensile tests on IN-519 are given in Table 13. The yield and ultimate tensile strengths are shown in Fig. 29. The alloy with the titanium addition (2357) is weaker at elevated temperatures than the alloy containing niobium (2356). Similar properties were shown in Fig. 2 for alloy 492, an alloy having a composition very near that of Inconel 617.

Y203305



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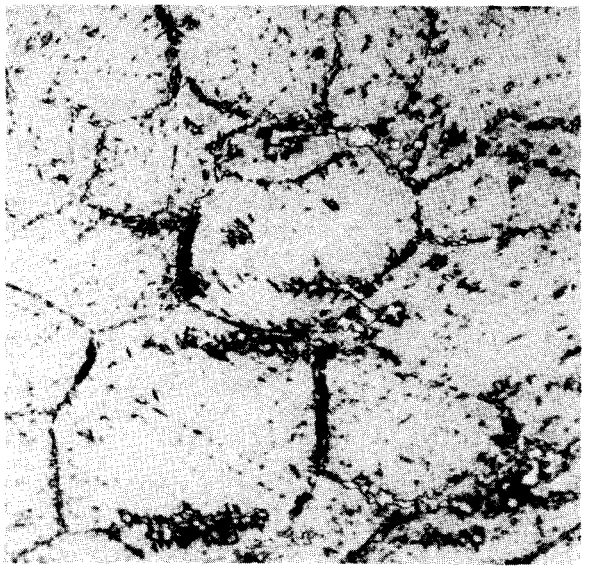

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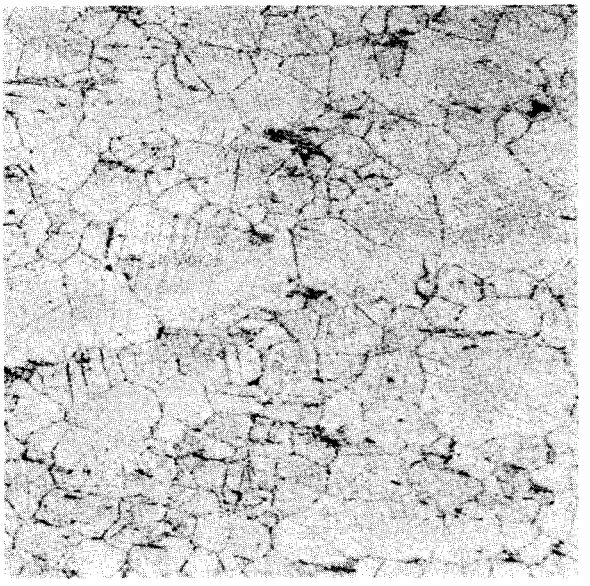
Fig. 25. Modified Inconel 617 alloy 801 after creep test 22214. Annealed 1 h at 1177°C and tested at 760°C and 138 MPa. Failed with 5.4% strain after 5714 h. (Photomicrographs located about 6 mm from fracture.)

Y203307



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Y203308

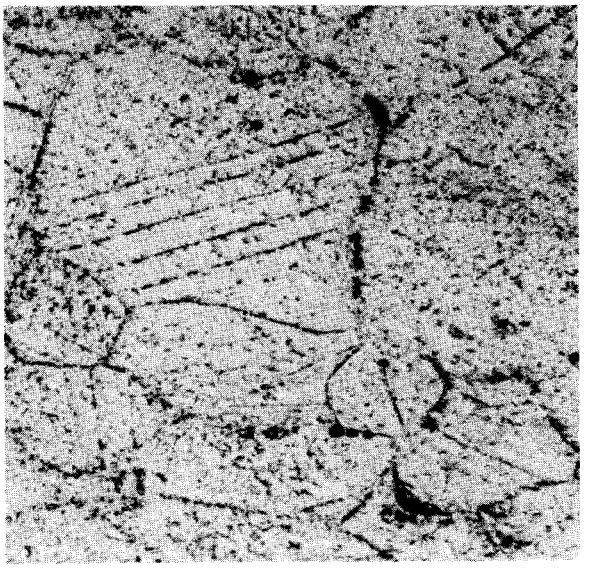

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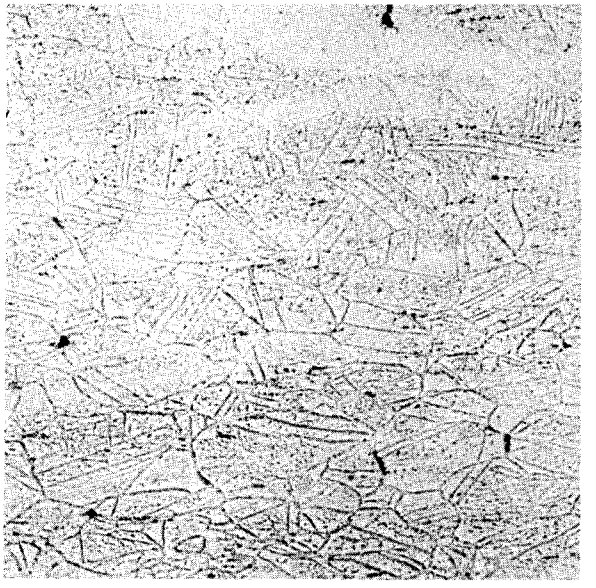
Fig. 26. Modified Inconel 617 alloy 803 after creep test 22220. Annealed 1 h at 1177°C and tested at 760°C and 138 MPa. Failed with 29% strain after 593 h. (Photomicrographs located about 6 mm from fracture.)

Y203309



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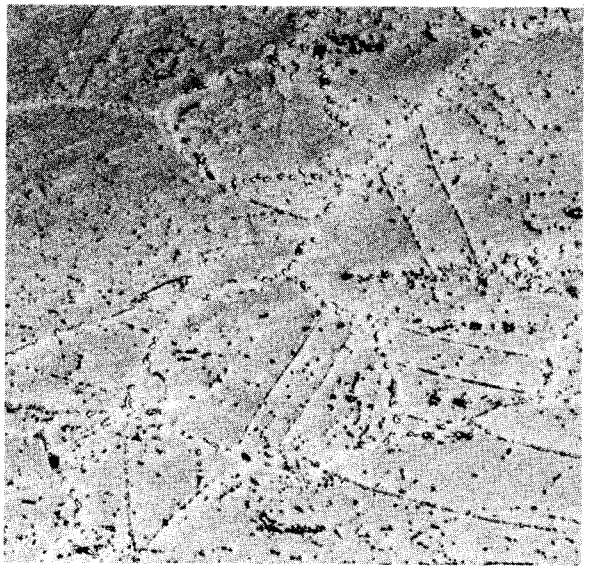
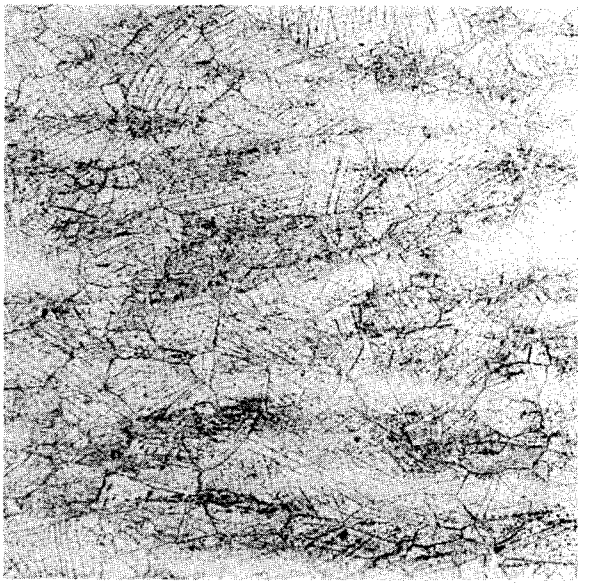


40 μm

Fig. 27. Modified Inconel 617 alloy 804 after creep test 22221. Annealed 1 h at 1177°C and tested at 760°C and 138 MPa. Failed with 44.5% strain after 514 h. (Photomicrographs located about 6 mm from fracture.)

Y203311



200 μm

Y203312

40 μm

Fig. 28. Modified Inconel 617 alloy 805 after creep test 2223. Annealed 1 h at 1177°C and tested at 760°C and 138 MPa. Failed with 32.1% strain after 703 h. (Photomicrographs located about 6 mm from fracture.)

Table 13. Tensile properties of IN-519 alloys 2356 and 2357

Test temperature		0.2% Yield strength		Ultimate tensile strength		Elongation (%)		Reduction of area (%)	Specimen type[a]	Failure location[a]
(°C)	(°F)	(MPa)	(ksi)	(MPa)	(ksi)	Uniform	Total			
					Alloy 2356 (Nb)					
25	77	321	46.5	554	80.4	17.0	17.0	17.4	B	
593	1100	192	27.9	371	53.8	16.3	16.7	14.4	B	
649	1200	207	30.0	375	54.4	12.5	12.8	16.7	B	
760	1400	190	27.5	294	42.7	7.4	7.5	6.9	B	
871	1600	211	30.6	308	44.6	11.9	12.3	20.2	B	
25	77	312	45.2	547	79.4	12.8	12.8	6.7	TW	B
871	1600	178	25.8	198	28.7	4.2	9.0	26.5	TW	B
					Alloy 2357 (Ti)					
25	77	264	38.3	552	80.0	20.7	20.7	20.3	B	
593	1100	145	21.0	189	27.4	3.0	3.1	3.0	B	
649	1200	157	22.8	230	33.4	4.0	4.7	3.6	B	
760	1400	189	27.4	269	39.0	8.7	32.5	53.0	B	
871	1600	192	27.8	265	38.4	8.2	11.2	28.7	B	
25	77	269	39.0	370	53.6	4.3	4.3	6.3	TW	W
871	1600	136	19.7	147	21.3	2.0	8.2	12.2	TW	W

[a]B = base metal, TW = transverse weld, W = weld metal.

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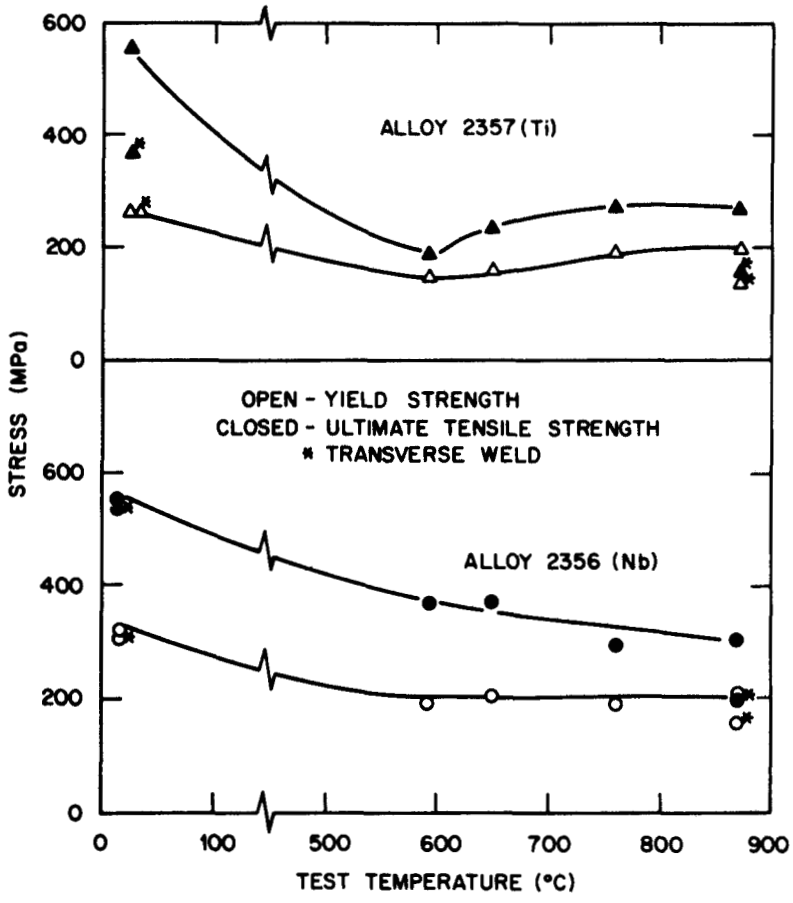

Fig. 29. Tensile properties of IN-519.

Note that IN-519 has a yield strength similar to that of alloy 492, but the ultimate tensile strength of IN-519 is much lower than that of alloy 492. The fracture strains of alloys 2356 and 2357 are shown in Fig. 30. The niobium-containing alloy (2356) had fracture strains between 7.5 and 17.5%, and the curve is quite smooth. The titanium-modified alloy (2357) had fracture strains from 3.5 to 32.5%, and the behavior with test temperature is quite erratic.

Fusion welds were prepared by making a transverse electron-beam weld in the gage section. As shown in Table 13, the samples of alloy 2356 failed in the base metal, and the samples of alloy 2357 failed in the weld metal. The samples failing in the base metal had fracture strains about equal to those of the base metal, and samples failing in the transverse-weld metal had fracture strains lower than those of the base metal. The

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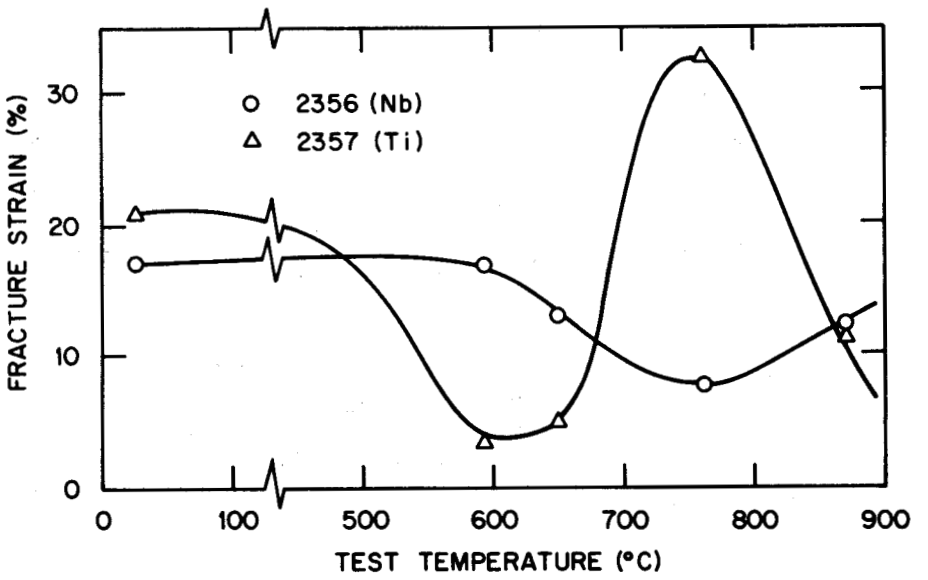

Fig. 30. Fracture strains of IN-519.

strengths of the transverse-weld specimens and of the base metal can be compared in Fig. 29. For alloy 2356, the strengths of base metal and transverse-weld metal were equivalent when tested at 25°C; when tested at 871°C, the welded sample was weaker. Transverse-weld samples of alloy 2357 were weaker than base-metal samples at test temperatures of 25 and 871°C.

Creep Test Results

The results of creep tests on alloys 2356 and 2357 are given in Table 14. In Fig. 31 these results are superimposed on a Larson-Miller plot from ref. 2. In the region of overlap, the data from the present study and those from the literature agree well. There is considerable scatter in the results, but alloy 2356 (niobium) appears to have higher creep strength than alloy 2357 (titanium). Several of the creep samples with transverse welds failed in the weld metal, but the rupture times are not significantly shorter than those of the base metal.

Metallographic Studies

Metallographic samples of the two alloys in the as-cast condition were prepared. Photomicrographs of alloy 2356 (niobium) are shown in

Table 14. Summary of creep tests on cast IN-519 alloys

(All tests in HTGR-He with no pretest anneal)

Test	Specimen type[a]	Test temperature		Stress		Time to (h)					Minimum creep rate (%/h)	Elongation (%)		Reduction of area (%)
		(°C)	(°F)	(MPa)	(ksi)	1% creep	2% creep	5% creep	Tertiary creep	Rupture		Loading	Creep	
							Alloy 2356							
21582[b]	B	649	1200	345	50	0.4				0.9	1.0 E+0	7.2	2.9	7.0
21585[b]	B	760	1400	103	15	80	200		190	439	6.5 E-3	0.06	6.0	17.8
22184	B	871	1600	69	10	250	430		210	605	5.0 E-4	0.05	8.6	13.0
21580	TW	871	1600	69	10					543			4.8[c]	16.2
21576	TW	871	1600	69	10					772			5.1	11.8
							Alloy 2357							
21584[b]	B	649	1200	276	40	0.2	2		5.5	7.7	3.0 E-1	4.3	5.1	12.6
22179[b]	B	760	1400	103	15	10	20	65	105	129	6.9 E-2	0.19	14.6	22.2
21583	B	871	1600	69	10	9	19	46	42	52	1.0 E-1	0.18	10.1	35.6
21581	TW	871	1600	69	10			2000	1920	8.6		0.05	6.6[c]	13.5
23333	TW	760	1400	69	10	120	250			2268	8.6 E-4		9.3[c]	17.7

[a]B = base metal; TW = transverse weld.

[b]Tested in air.

[c]Failed in weld metal.

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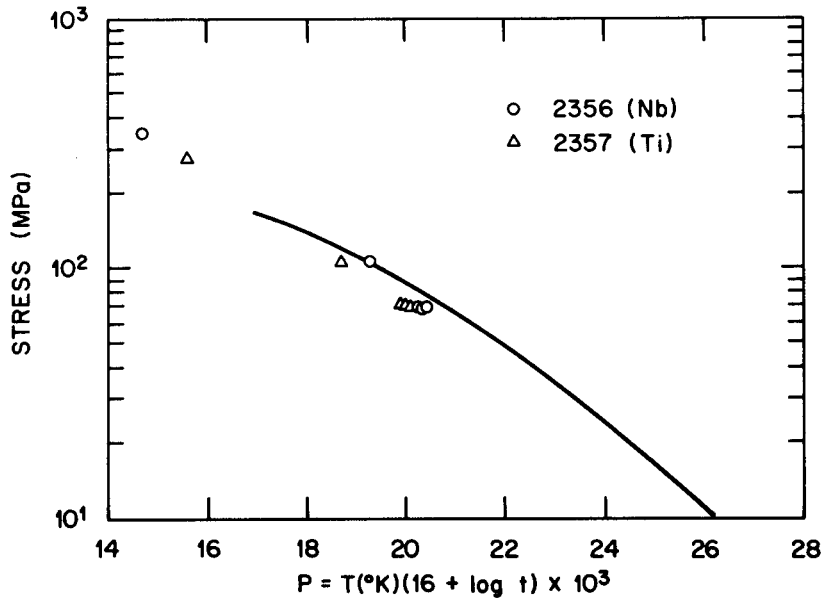

Fig. 31. Larson-Miller correlation for IN-519. The points are from ORNL data; the line is from *IN-519 Cast Chromium-Nickel-Niobium Heat-Resisting Steel*, INCO Databook Service, copyright 1976, INCO, Inc., One New York Plaza, New York, NY 10004.

Fig. 32. The microstructure is quite fine, and the dominant constituent is the interdendritic eutectic niobium carbide and chromium carbide.[2] The dendrite size is about the same in alloy 2357 (titanium, Fig. 33) as in alloy 2356; however, the interdendritic material does not appear to be a eutectic product.

Carbon Analyses of Tested Samples

Alloy 2356 contained 3000 ppm carbon, and alloy 2357 contained 2500 ppm carbon. Six test samples run as long as 5500 h at 871°C were analyzed for carbon. The analyzed samples had carbon concentrations within ±8% of those of the as-received material. Thus, the changes were insignificant compared with the high initial values.

CABOT ALLOY 214

Sources

The material for this study was procured from Cabot Corporation in the form of hot-rolled plate 1.3 cm (0.5 in.) thick. The weld wire used

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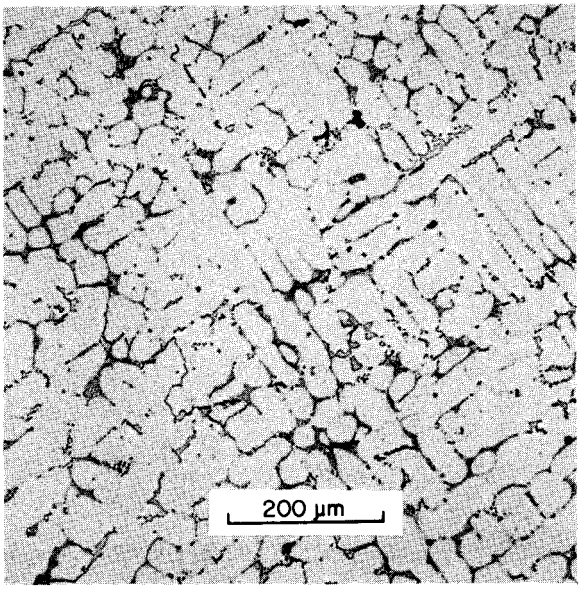

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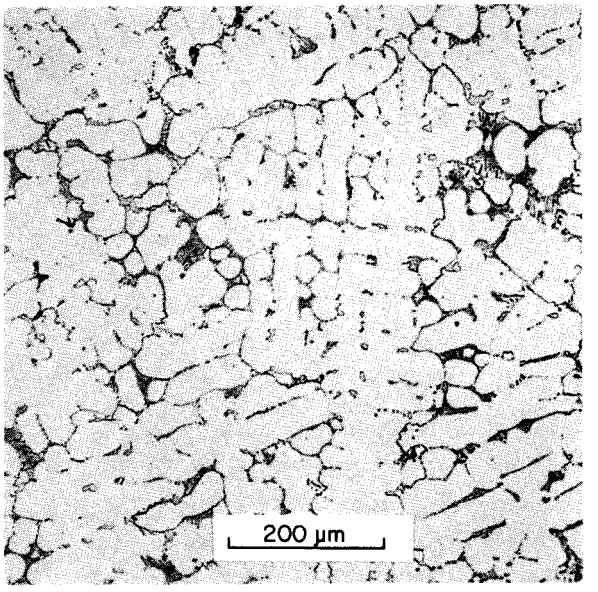

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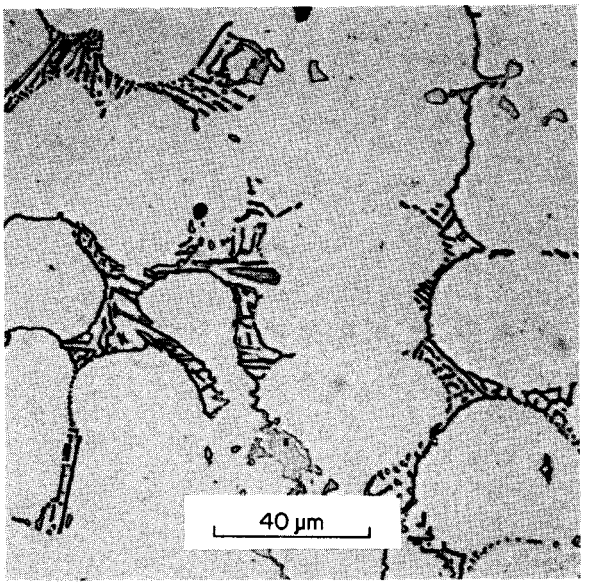

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Fig. 32. IN-519 alloy 2356 as received. (*a*) Transverse view. (*b*, *c*) Longitudinal views.

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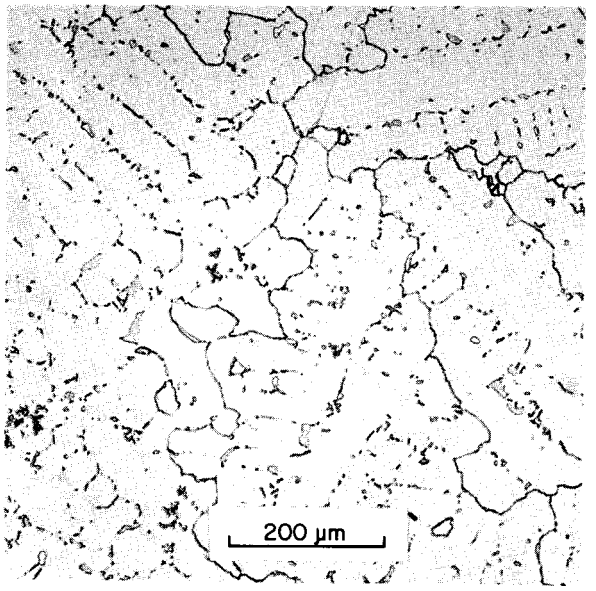

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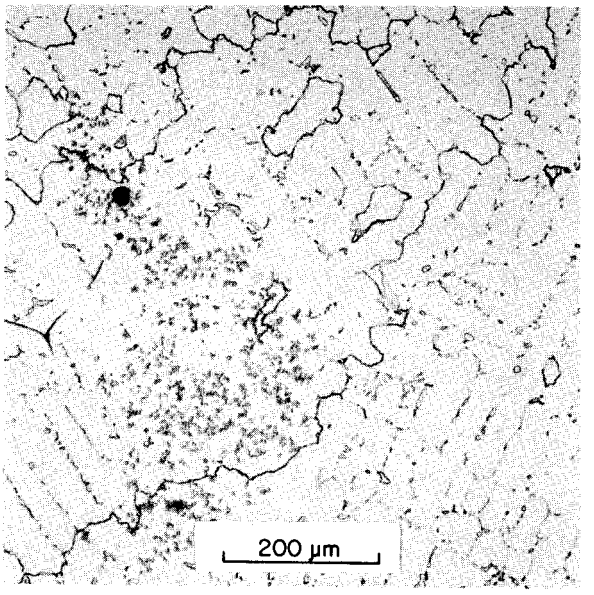

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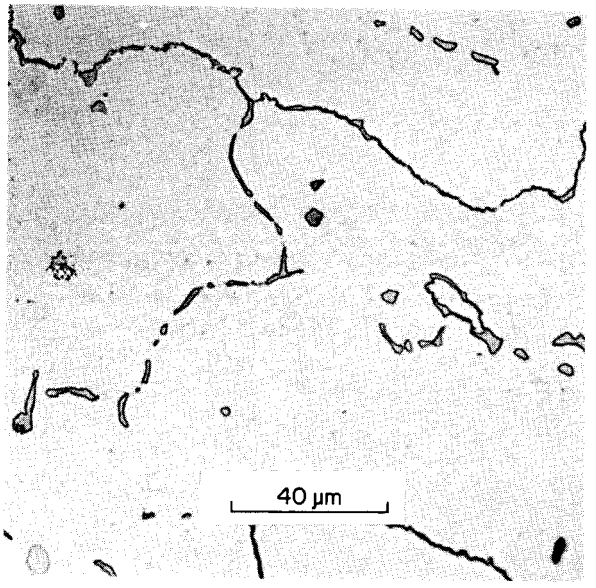

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Fig. 33. IN-519 alloy 2357 as received. (*a*) Transverse view. (*b*, *c*) Longitudinal views.

was 0.40 cm (0.156 in.) in diameter and was also obtained from Cabot. The chemical analyses of both materials are given in Table 1. Tensile and creep specimens were prepared so that the gage length was all base metal, was all weld metal, or contained a transverse weld through the base metal.

Tensile Test Results

The results of tensile tests on alloy 214 are given in Table 15. The yield and ultimate tensile strengths are plotted in Fig. 34. The yield strength holds up well with temperatures to above 750°C. The ultimate tensile strength decreases gradually to a test temperature above 750°C and drops more rapidly at higher test temperatures. Transverse welds are generally weaker than the base metal. The fracture strain of the alloy is shown in Fig. 35. The alloy has a ductility minimum of about 5% at 750°C. Samples of weld metal and transverse welds have fracture strains lower than those of the base metal.

Impact Test Results

Charpy-V impact samples with the notch in the base metal and in the weld metal were aged in an inert environment and tested at 25°C. The results are given in Table 16. The material aged in a short time at 871°C, and the impact energy of the base metal dropped from 180 to 11.6 J after aging only 100 h at 871°C; however, after aging the base metal at 871°C for 1000 h, the impact energy had improved to 33.6 J. Thus, the alloy seems to age and overage very rapidly at 871°C on the basis of impact properties. Aging the base and weld metal at 704°C for 1000 h resulted in impact energies of 10.9 and 11.2 J, respectively. Thus, this alloy is susceptible to aging, and the minimum impact values and times associated with each temperature are not known.

Creep Test Results

Several creep tests were run on the alloy, and the results are summarized in Table 17. The rupture times of these tests are compared in Fig. 36 with the results from the manufacturer's literature.[3] The test results from our study for base metal show that our product had somewhat higher strength than the material evaluated by the manufacturer. Weld

Table 15. Tensile properties of Cabot alloy 214

Test temperature		0.2% Yield strength		Ultimate tensile strength		Elongation (%)		Reduction of area (%)	Specimen type[a]	Failure location[a]
(°C)	(°F)	(MPa)	(ksi)	(MPa)	(ksi)	Uniform	Total			
25	77	615	89.2	919	133.3	34.5	35.0	48.9	B	B
25	77	569	82.6	815	118.2	21.2	21.7	49.5	TW	W
25	77	537	77.9	746	108.2	15.3	16.3	30.3	W	W
25[b]	77	561	81.3	889	128.9	39.9	37.5	49.9	B	B
25[c]	77	524	76.0	840	121.8	27.4	28.0	39.6	B	B
538	1000	572	82.9	774	112.2	28.6	29.1	31.7	B	B
538	1000	507	73.6	684	99.2	27.8	29.0	43.1	W	W
593	1100	572	82.9	698	101.2	14.5	15.5	18.6	B	B
649	1200	550	79.7	650	94.3	7.3	7.9	19.5	B	B
649[c]	1200	470	68.2	621	90.1	16.3	16.7	30.0	B	B
649	1200	507	73.5	554	80.3	3.7	4.3	23.3	TW	W
649	1200	471	68.3	482	69.9	3.1	4.7	20.1	W	W
704	1300	554	80.3	610	88.5	4.8	5.1	14.7	B	B
760	1400	520	75.4	543	78.7	4.2	4.7	7.7	B	B
760	1400	481	69.8	490	71.0	4.3	4.9	6.9	W	W
871	1600	362	52.5	366	53.1	0.7	15.1	18.6	B	B
871	1600	328	47.5	339	49.2	0.7	6.1	3.1	TW	W
871	1600	339	49.2	345	50.0	0.3	6.1	6.1	W	W

[a]B = base metal, TW = transverse weld, W = weld metal.

[b]Annealed 1 h at 1177°C in argon.

[c]Annealed 1 h at 1177°C plus 24 h at 982°C in argon.

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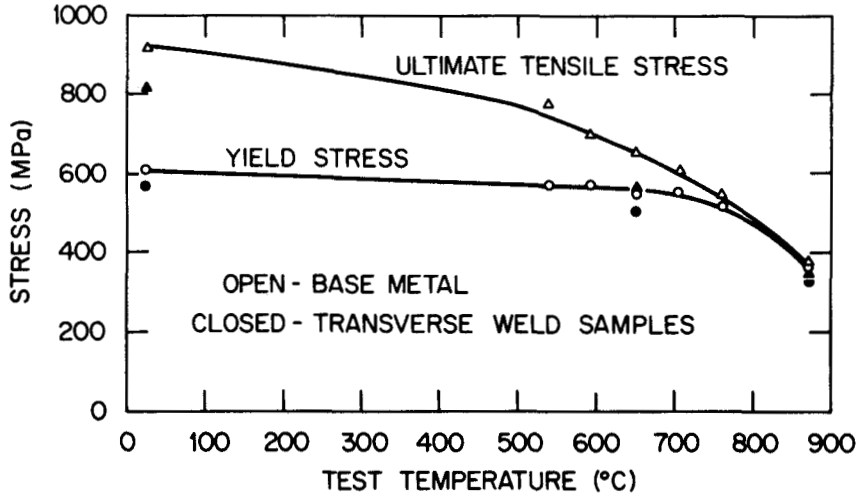

Fig. 34. Tensile properties of Cabot alloy 214 in the hot-worked condition.

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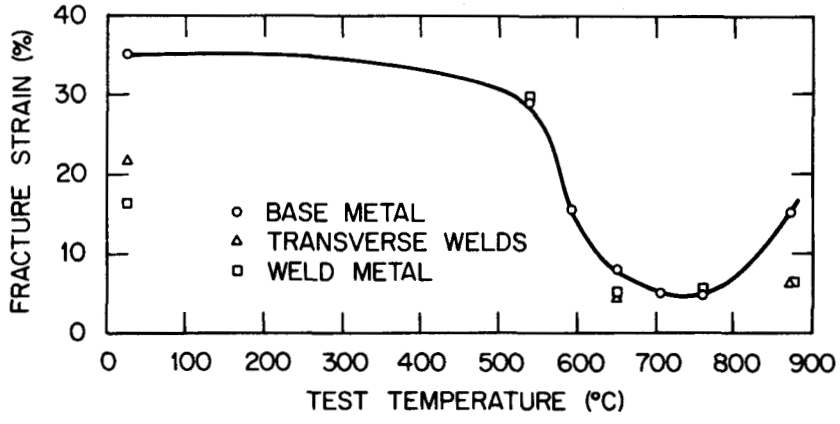

Fig. 35. Fracture strains of Cabot alloy 214 samples in short-term tensile tests.

metal was quite weak, and samples made entirely of weld metal or those with transverse welds failed in much shorter times than those required for base metal. Samples of base metal and weld metal had fracture strains of 2% or less at test temperatures of 649 and 760°C. At 871°C the base metal failed after about 8% strain, and weld samples continued to have fracture strains of 2% or less.

Table 16. Results of Charpy-V impact tests on Cabot alloy 214 at 25°C

Specimen type	Treatment	Impact energy (J)
Base metal	As received	180
Weld metal	As received	119
Base metal	100 h at 871°C in argon	11.6
Weld metal	100 h at 871°C in argon	15.0
Base metal	1000 h at 871°C in argon	33.6
Weld metal	1000 h at 871°C in argon	29.2
Base metal	1000 h at 704°C in argon	10.9
Weld metal	1000 h at 704°C in argon	11.2

Metallographic Studies

The microstructure of the as-received material is shown in Fig. 37. The material was supplied in the as-hot-worked condition, and the only microconstituent is a few stringers of very fine precipitate. The composition of this alloy is such that heating it should cause the formation of gamma prime internally and an alumina surface oxide containing a small amount of Y_2O_3. Micrographs of a sample tested 5759 h at 871°C in HTGR-He are shown in Fig. 38. The microstructure is consistent with the formation of gamma prime within the specimen and a very complex surface oxide. The oxide seems to penetrate along grain boundaries, and the depth of oxide is 0.4 mm at the location shown in Fig. 38.

Carbon Analysis of Tested Sample

Only one posttest carbon analysis was available for this alloy. The sample from test 23849 ran 5759 h at 871°C in HTGR-He. Duplicate carbon analyses on the as-received material gave values of 0.035 and .037 %, and duplicate samples on the creep sample from test 23849 gave values of 0.39 and 0.37%. Thus, the test sample was heavily carburized.

Table 17. Summary of creep tests on Cabot alloy 214

Test	Specimen type[a]	Environment	Time to (h)				Minimum creep rate (%/h)	Elongation (%)		Reduction of area (%)
			1% creep	2% creep	Tertiary creep	Rupture		Loading	Creep	
Test temperature 649°C (1200°F); stress 345 MPa (50 ksi)										
23854	B	Helium	6		5.5	6.6	2.9 E-2	0.21	2.0	0.8
24186	B	Air				370	5.8 E-3	0.19	1.6	2.5
24187	TW	Helium				12.9		0.03	2.1[b]	0.3
Test temperature 760°C (1400°F); stress 138 MPa (20 ksi)										
24316	B	Helium				97.7	2.1 E-3		0.6	0.0
24198	B	Air			770	859	7.8 E-5	1.6	1.1	1.1
24318	TW	Helium				7.2		0.02	1.9[b]	3.1
Test temperature 871°C (1600°F); stress 48 MPa (7 ksi)										
23849	B	Helium	3200	4500	2700	5759	8.0 E-5	0.03	8.0	14.0
23850	B	Air				1433	1.1 E-4		7.6	3.6
23852	TW	Helium				24.5	9.6 E-4		1.8[b]	1.1
23848	W	Helium				17.0	3.3 E-3		0.9	1.0

[a]B = base metal; TW = transverse weld; W = weld metal.

[b]Fractured in weld metal.

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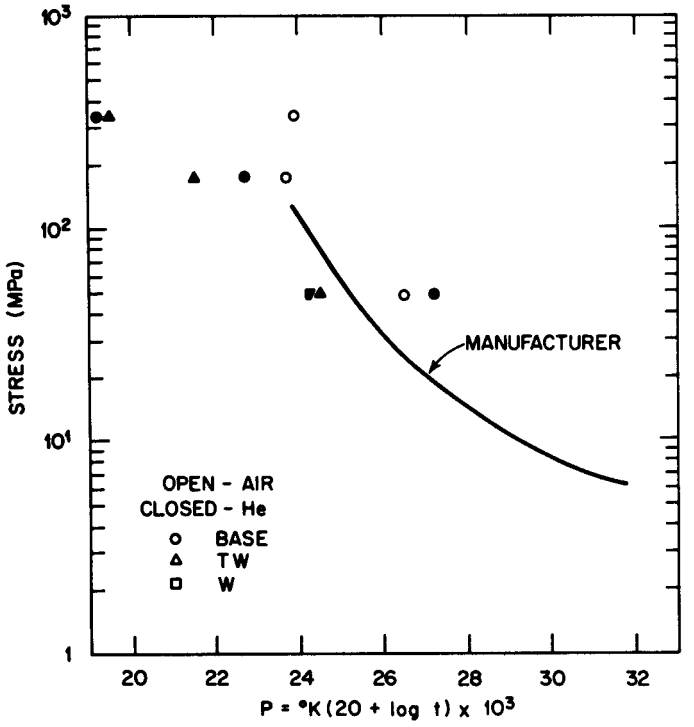

Fig. 36. Larson-Miller correlation for Cabot alloy 214, based on the time to failure. The points are from ORNL data; the line is from *Cabot Alloy 214*, Cabot Corporation, Kokomo, IN 46901, May 1983.

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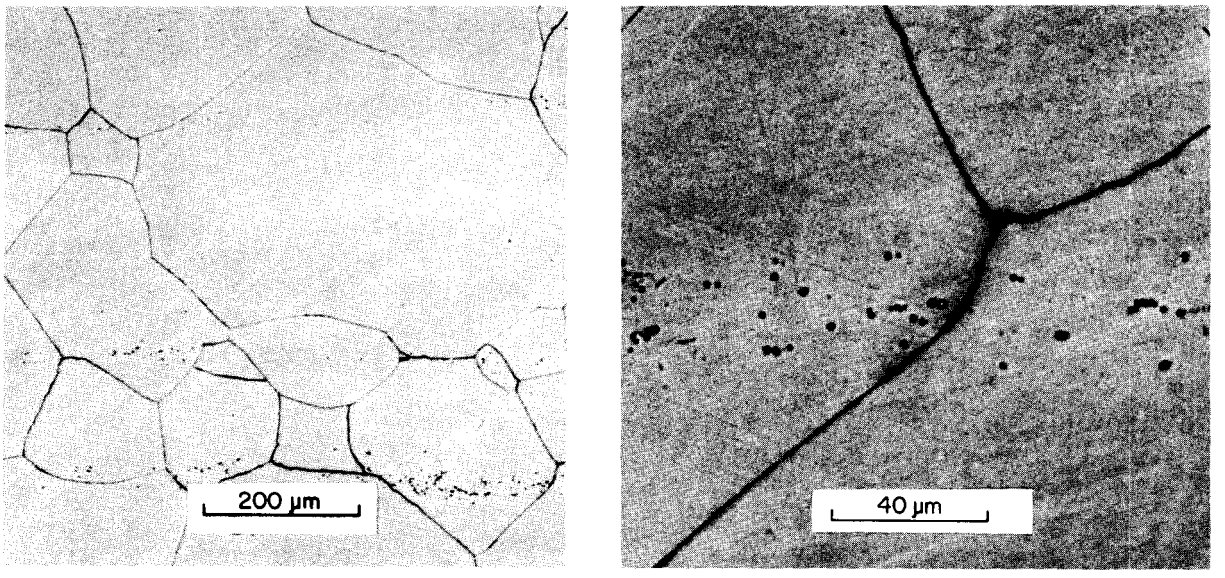

Fig. 37. Longitudinal views of Cabot alloy 214 in the as-hot-worked condition.

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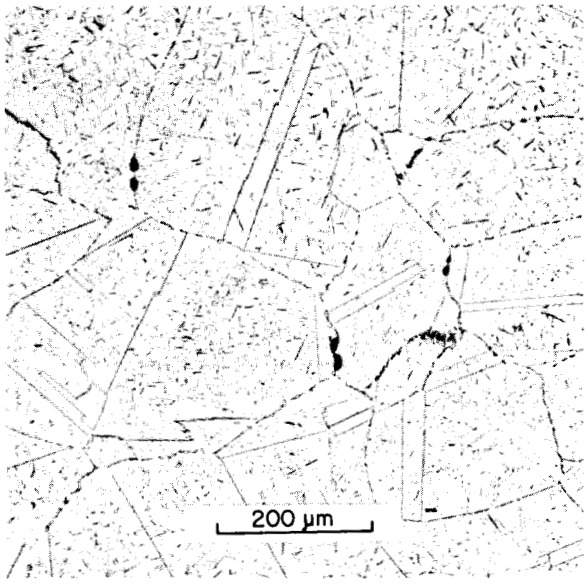

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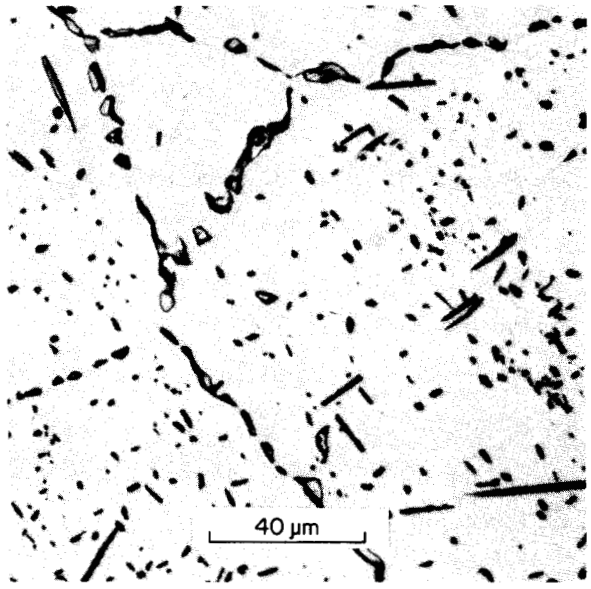

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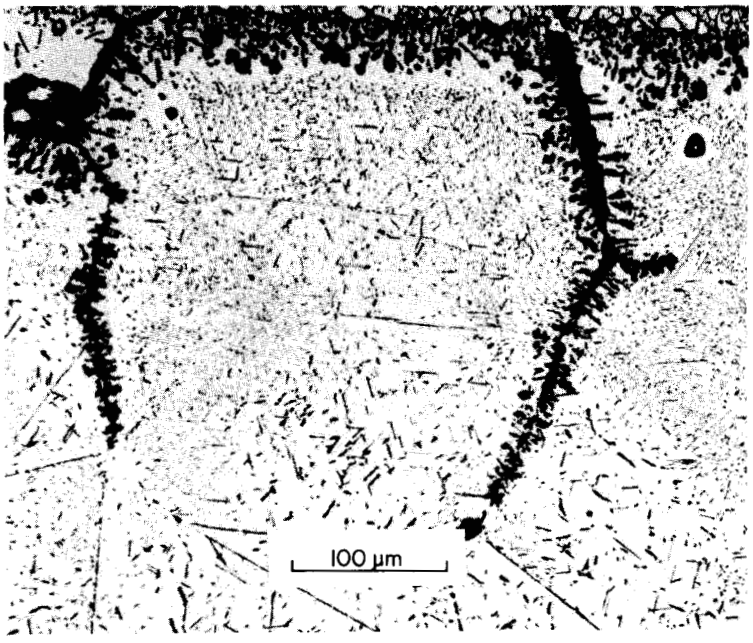

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Fig. 38. Cabot alloy 214 after creep test 23849. Test conditions were 871°C and 48 MPa in HTGR-He. Failed after 5759 h. (*a*, *b*) Transverse views. (*c*) Edge view of oxide.

ALLOYS GA 911 AND GA 912

Source

ORNL was provided five 18.4-cm (7 1/4-in.) lengths [~1.3 cm (1/2 in.) in diam] of solution-annealed GA Technologies experimental alloys GA 911 and GA 912. The nominal compositions of these alloys were Ni–8% Cr–10% Mo–2% Al–2% Ti for GA 911 and Ni–8% Cr–10% W–2% Al–2% Ti for GA 912. The alloys were heat treated by GA Technologies to provide similar grain sizes of about 250 μm for both alloys. Alloy GA 912 was solution annealed at 1125°C for 30 h and water quenched, and alloy GA 911 was solution annealed at 1125°C for 10 h and water quenched. The product had rather large surface hot cracks, but the cracked material was removed in making test samples.

Creep Test Results

All creep tests on these materials were performed in HTGR-He, and the results are given in Table 18. All nine of the tests are completed on alloy 911, and one test is still in progress on alloy 912. The data in Table 18 show the trend of increasing fracture strain with increasing test temperature. The Larson-Miller parameter with a selected constant of 20 was used to correlate the test results for 1% strain and rupture. The results for 1% strain are shown in Fig. 39. There is no systematic strength variation of one alloy over another, but two points for alloy 911 scatter to the strong side and one point for alloy 912 scatters to the weak side. Data for the time to rupture are shown in Fig. 40. The results exhibit considerable scatter, but there is not a strong tendency for one alloy to be stronger than another.

Metallographic Studies

Samples from the next to longest tests at the highest temperature on alloys 911 and 912 were examined metallographically. Typical photomicrographs of alloy 911 are shown in Fig. 41. The oxide formed on the surface and along the grain boundaries to a depth of about 0.3 mm. The morphology noted would be expected on the basis of the high titanium and aluminum content and the service temperature of 950°C. The etched photomicrographs were made about 6 mm from the fracture. The second

Table 18. Summary of creep data on alloys GA 911 and GA 912 tested in the solution-annealed condition in HTGR-He

Test	Temperature (°)	Stress (MPa)	Stress (ksi)	Time to (h) 1% creep	2% creep	5% creep	Tertiary creep	Rupture	Minimum creep rate (%/h)	Creep Strain (%)	Reduction of area (%)
						Alloy 911					
23357	850	138	20	245	310	400	210	505	1.2 E-3	18.5	39.2
23829	850	103	15	644	1,030	1,400	800	1,636	8.3 E-4	16.1	35.0
23842	900	103	15	40	58	88	40	133	1.8 E-2	24.4	49.0
23358	900	69	10	863	1,370	1,810	1,240	2,191	8.4 E-4	24.5	86.8
23845	900	48	7	1,600	1,990	2,270	1,700	2,594	3.7 E-4	15.2	46.0
23596	950	48	7	40	50	67	37	85	1.3 E-2	18.9	25.1
23599	950	35	5	110	142	200	110	431	4.6 E-3	35.6	41.3
23606	950	28	4	385	450	600	350	1,537	1.3 E-3	49.9	75.0
23828	950	21	3	1,170	1,370	1,780	1,150	3,280	3.7 E-4	42.4	54.5
						Alloy 912					
23837	850	138	20	255				324	2.9 E-3	17.2	36.1
23836	850	103	15	115	785		738	994	7.6 E-4	8.1	20.3
23362	900	69	10	213	250	300	180	325	1.4 E-3	11.8	31.1
23846	900	48	7	510	630	850	430	1,228	5.4 E-4	17.3	23.7
23597	950	48	7	60	75	100	54	163	5.0 E-3	26.5	43.0
23602	950	35	5	130	170	255	105	477	3.0 E-3	26.4	26.0
23617	950	28	4	334	435	700		3,745		30.4	42.7
23831	950	21	3	1,400	2,300	3,900	2,000	12,356	7.1 E-4	40.5	22.7

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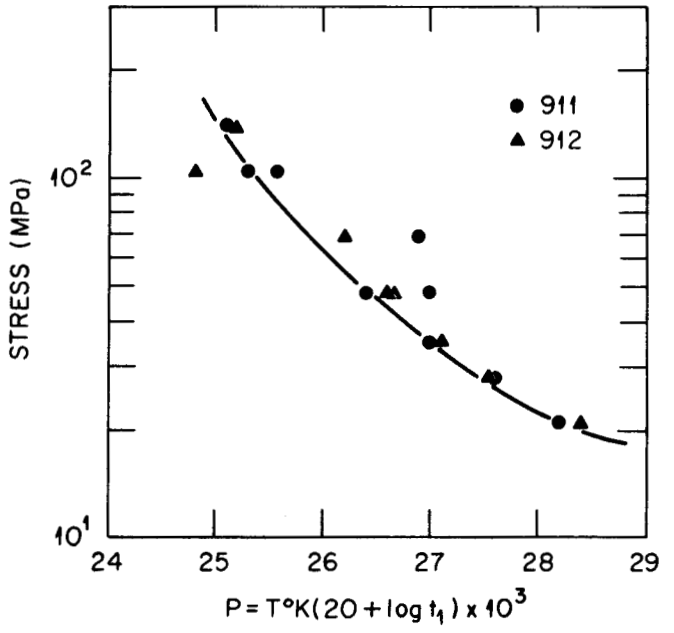

Fig. 39. Larson-Miller plot for the time to 1% strain for alloys GA 911 and GA 912.

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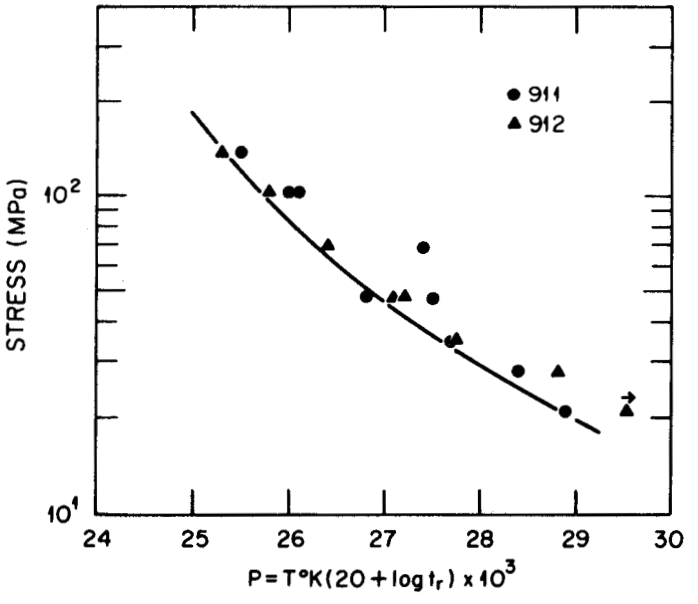

Fig. 40. Larson-Miller plot for the rupture of alloys GA 911 and GA 912.

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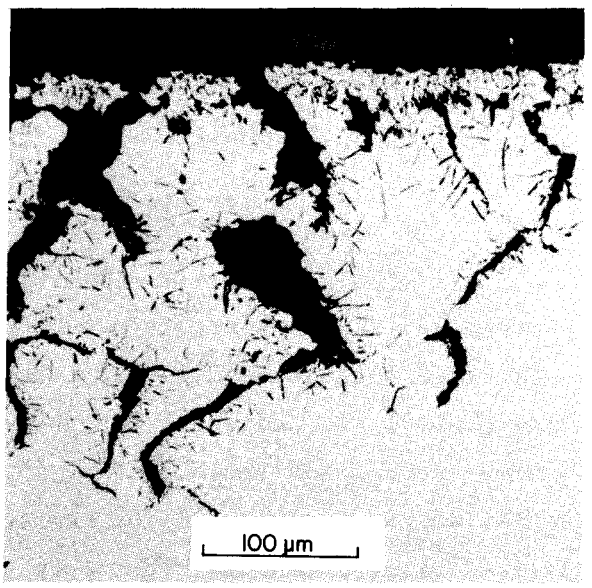

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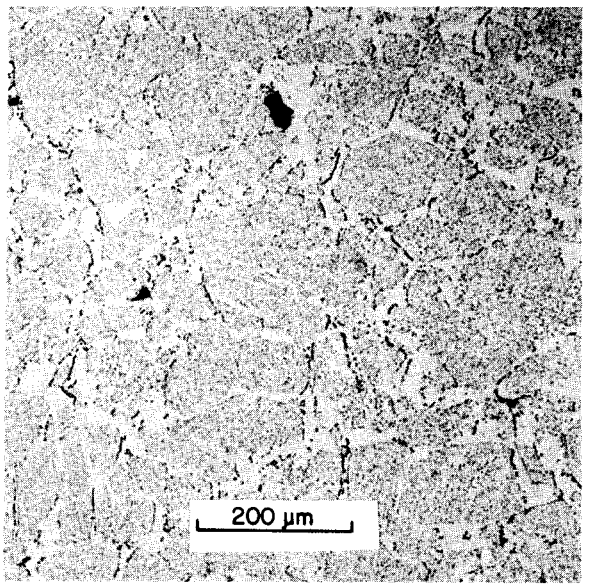

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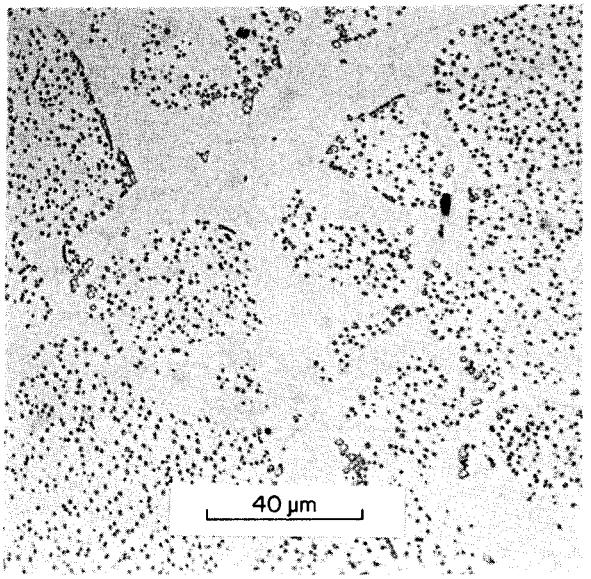

(*c*)

Fig. 41. Alloy GA 911 after creep test 23606. Tested in HTGR-He at 950°C with a stress of 28 MPa. Failed after 1537 h. (*a*) Edge near fracture, showing oxide. (*b*, *c*) Typical longitudinal sections.

phase was not analyzed but is likely gamma prime. Microstructures typical of alloy 912 after testing at 950°C are shown in Fig. 42. This sample also has an oxide layer of the order of 0.3 mm. The phase revealed upon etching is somewhat different from that noted in Fig. 41 for alloy 911, but this may be due to the longer test time of the sample shown in Fig. 42.

Carbon Analyses of Tested Samples

Five samples were sent for carbon analyses, and the results are shown in Fig. 43. Duplicate determinations were made for each sample, and there was considerable scatter of test results. This would indicate that the carbon content of the material was not homogeneous. As shown in Fig. 43, the HTGR environment carburized one sample, was neutral toward one sample, and decarburized three. Thus, these limited results indicate that both alloys had a high degree of resistance to carburization.

DISCUSSION OF RESULTS

Several alloys were evaluated previously for the high-temperature portions of HTGRs. They include Hastelloy X (ref. 4), Inconel 617 (ref. 5), Inconel 618 (ref. 5), HD 556 (ref. 6), and Incoloy 802 (ref. 6). These alloys have their advantages and disadvantages. Hastelloy X is a well established material with moderate creep strength, but it ages (with resultant low impact energy at ambient temperature) and carburizes. Inconel 617 is also a well established alloy and has higher creep strength than Hastelloy X. Inconel 617 fails after only 1 to 2% creep strain at about 650°C but is more ductile at higher temperatures. Inconel 617 ages more slowly than Hastelloy X but eventually ends up with equally low impact energies at ambient temperature. Rather limited data indicate that Inconel 617 carburizes more rapidly than Hastelloy X. Inconel 618 is the most stable alloy evaluated, with only minimal property changes due to aging. Inconel 618 has about the same creep strength as Hastelloy X and carburizes at a rate between that of Inconel 617 and Hastelloy X. HD 556 is still classified as an experimental alloy. It has creep strength about equivalent to that of Inconel 617, but it ages and has low impact strength

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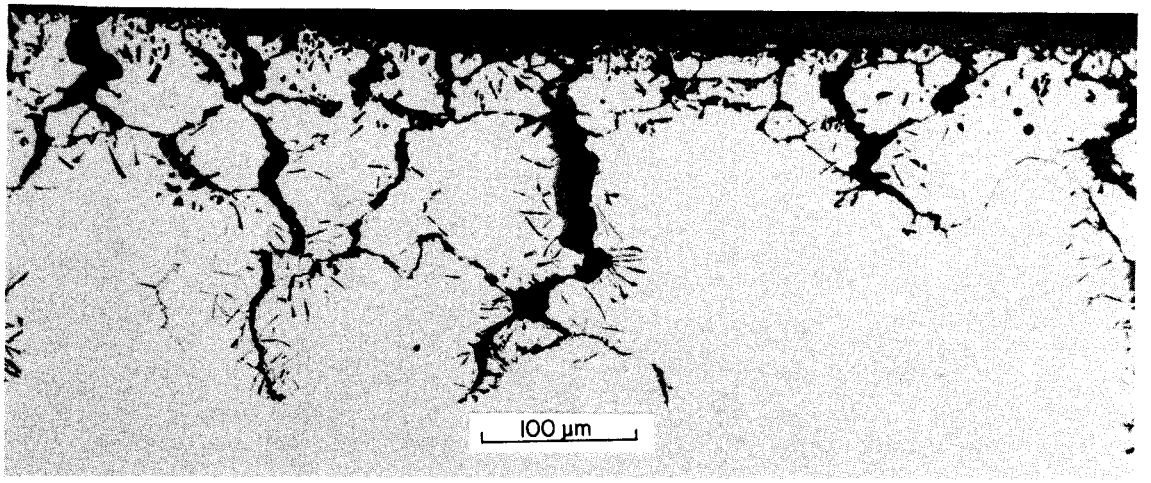

(*a*)

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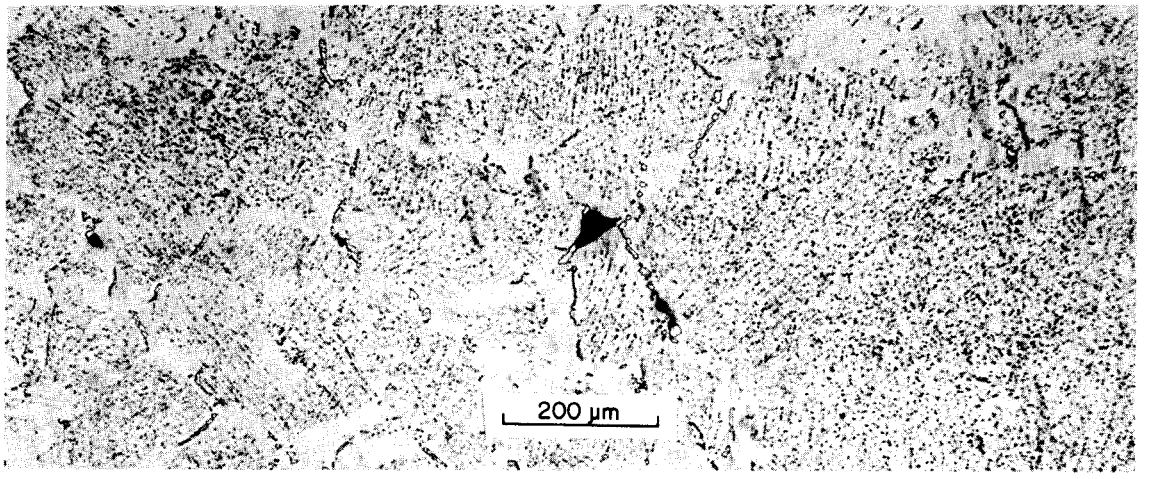

(*b*)

Fig. 42. Alloy GA 912 after test 23617. Tested in HTGR-He at 950°C with a stress of 28 MPa. Failed after 3745 h. (*a*) Edge near fracture, showing oxide. (*b* and *c*) Typical longitudinal sections.

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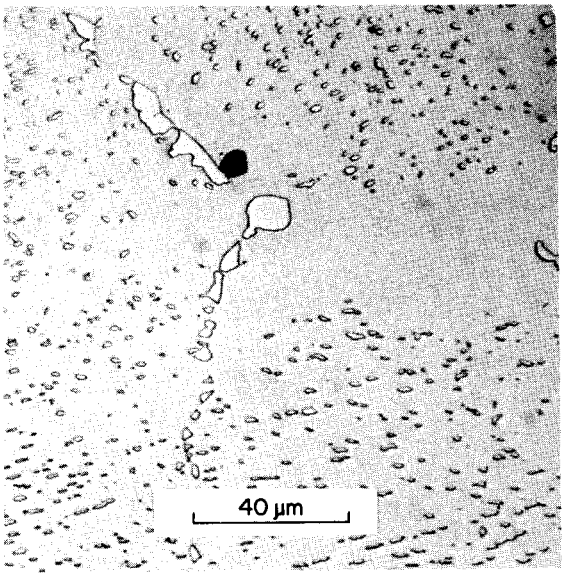

(c)

Fig. 42 (Continued)

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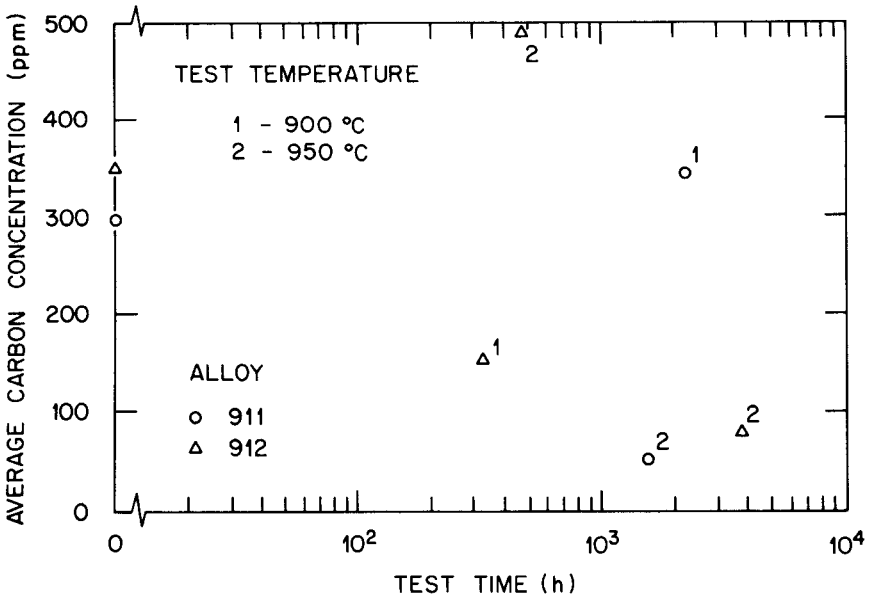

Fig. 43. Variation of average carbon concentration for alloys GA 911 and GA 912 as a function of test conditions.

at ambient temperature. HD 556 contains a small amount of lanthanum, which apparently helps form an impervious oxide that slows or prevents carburization. Incoloy 802 has a nominal carbon content of 0.3%, which leads to high creep strength and poor ductility and weldability.

Some of these alloys could be used in spite of their limitations, but considerable improvement in service reliability could be obtained by working on the weaknesses of the alloys just described. The most desirable alloy would have high creep strength, would not change properties appreciably during aging, and would be resistant to carburization. Chemical modifications were made to the basic composition of Inconel 617 in an effort to achieve some improvement over standard Inconel 617. The modifications made were reduction in chromium level and addition of about 2% titanium or aluminum to obtain a more impervious oxide film that would be more resistant to carburization.

Modified Inconel 617 alloys 492, 493, and 494 (see Table 1) were obtained from a commercial vendor and were studied rather extensively. The creep strength for these three alloys based on 1% creep strain is shown in Fig. 44. The three alloys have the same strength even though the chromium content varies from 12 to 22%. A composite Larson-Miller plot of most of the alloys studied is shown in Fig. 45. Note that the line based on alloys 492, 493, and 494 (labeled "modified 617" in Fig. 45) falls below the line for standard Inconel 617, and the lines are diverging at higher parameters (higher temperature or longer time). The lower strength may have been due to the modified alloys being cleaner. The data in Tables 7 through 9 show that the modified alloys have very high fracture strains. The impact data in Table 6 show that the modified alloys are subject to an aging reaction that peaks at 704°C and decreases in magnitude with decreasing chromium content. The lowest value obtained was 24 J for alloy 492 after aging 10,000 h at 704°C. This is close to values noted for standard Inconel 617. The carbon analyses are shown in Fig. 8, and some statistical parameters are shown in Table 10. With the rather high scatter of the test results, it is questionable whether any of the alloys exhibited measurable carburization. Standard Inconel 617 would carburize under these conditions. The difference in behavior is likely due to the titanium addition and not due to the variation in chromium from 12 to 22%.

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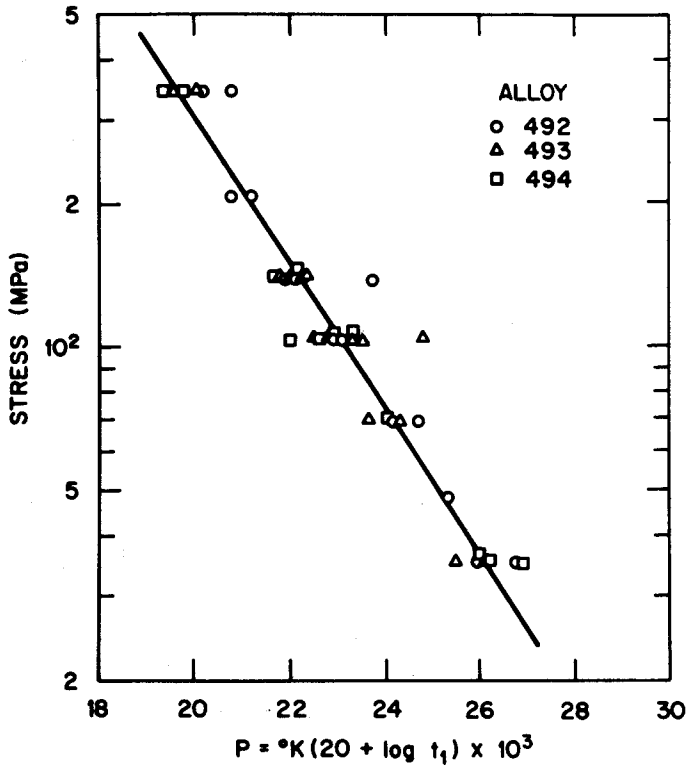

Fig. 44. Larson-Miller correlation for three modified Inconel 617 alloys based on 1% creep.

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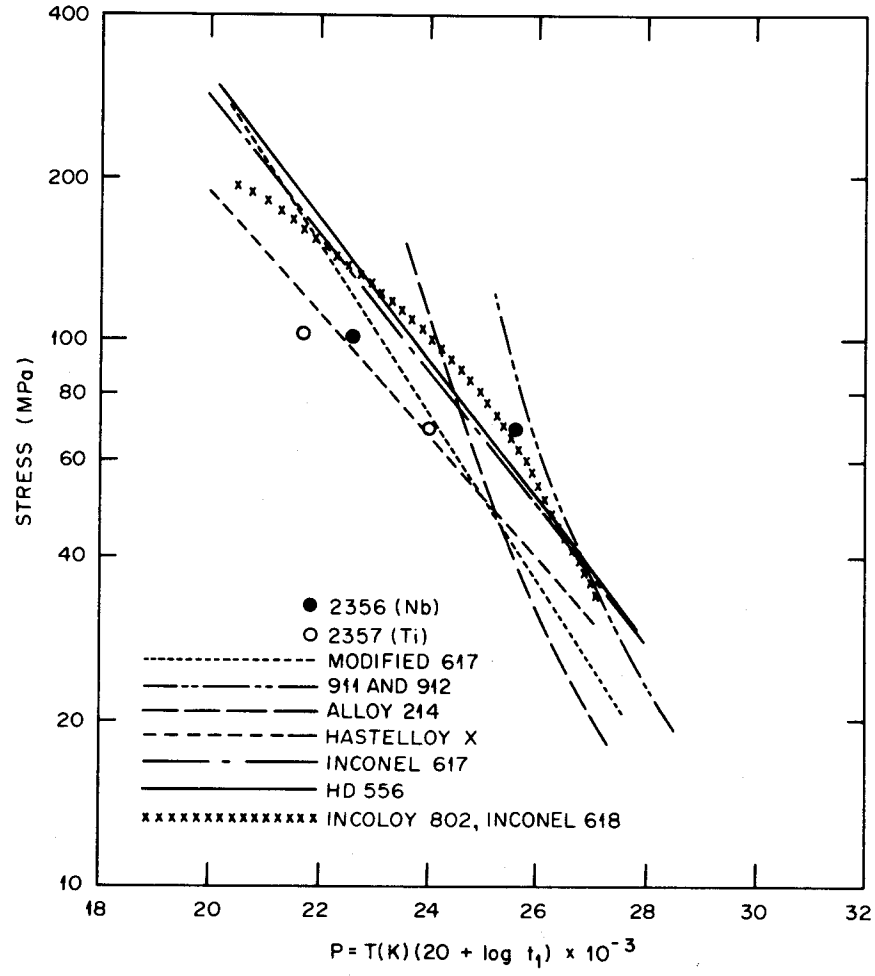

Fig. 45. Comparison of stress to produce 1% strain in several alloys.

Another series of alloys was prepared with variations in Al, Ti, and Cr but having the basic composition of Inconel 617. The amount of material available for each alloy was only enough to make a few samples. The mechanical properties of the alloys were dominated by the presence or absence of gamma prime, and the chromium concentration did not have a detectable effect. Too few samples received enough exposure for the carbon analyses to allow a conclusion about resistance to carburization.

IN-519 is a very special alloy that could be used for some parts that could be centrifugally cast. The alloy normally contains about 1.5% niobium. We statically cast samples containing niobium and one containing titanium, but the properties of the material containing 1.5% niobium were the most desirable. The creep data for these two alloys are limited, but two points for each alloy are shown in Fig. 45. The niobium-containing alloy appears to be almost as strong as the high-nickel alloys, and the alloy containing titanium is almost as strong. These alloys contain about 0.3% carbon, and no change could be detected after exposure to HTGR-He. The carbon concentration of alloy 2356 (Nb) and 2357 (Ti) was 3000 to 4000 ppm. Six test samples reached 5500 h at 871°C, and the carbon concentration varied only ±8% of the initial value. Thus, these alloys seem quite resistant to carburization.

Cabot alloy 214 is a developmental alloy and contains a small amount of yttrium for oxidation resistance. Our tests indicated that the alloy undergoes an aging reaction very rapidly at 871°C and more slowly at lower temperatures. The aging reaction results in Charpy V impact energies as low as 11.6 J. The weld metal of this material was quite weak. Creep tests run at ORNL and others run by the vendor were used to construct the line shown in Fig. 45. At high stresses, alloy 214 creeps more slowly than Hastelloy X, but alloy 214 is weaker at low stresses than Hastelloy X. Carbon was analyzed only in the sample from test 23849. This sample was exposed to HTGR-He for 5759 h at 871°C, and the carbon content increased from 360 to 3800 ppm. Thus the carburization rate appears to be quite high. The weld metal in this alloy was quite weak, and samples with transverse welds failed at low stresses.

Alloys GA 911 and GA 912 were quite strong at the lower test temperature of 850°C but were weaker than Inconel 617 and HD 556 at 950°C.

These alloys seemed to resist carburization, and there was very little evidence of carbon change in the test samples.

SUMMARY AND CONCLUSIONS

The alloys studied in this series offer several indications about alloy behavior in HTGR systems. (1) Most nickel-and-iron-base alloys are subject to some type of aging, which results in a reduction of the impact energy at ambient temperatures. For most alloys this is caused by carbide precipitation, and some alloys contain enough titanium and aluminum to form gamma prime. There likely are other intermetallic compounds that play a role in this aging process. Thus, this type of embrittlement is worsened by increasing levels of C, Ti, Al, Nb + Ta, and Cr. (2) Control of carburization through bulk chemistry seems to be difficult when alloys contain several percent of strong carbide formers such as chromium. The most promising approach thus far is to add elements that are active in forming less permeable oxides, such as titanium and lanthanum (HD 556). (3) The matter of creep strength seems rather straightforward. At temperatures of 600 to 700°C, gamma prime, carbide precipitation, and numerous other mechanisms can increase the creep strength. At higher temperatures, diffusional creep processes control creep. Here the amount of solute in solution and its melting point are very important. The two strongest alloys at the higher test temperatures are Inconel 617 and HD 556, both of which contain cobalt. Molybdenum and tungsten are effective solution-strengthening elements but do not seem to be as effective as cobalt.

The reason for the cleaner alloys of modified Inconel 617 being weaker than commercial Inconel 617 is not known; however, this type of weakness is quite often noted when small amounts of an alloy are prepared from virgin melting stock. The residual elements or larger amount of working may be responsible for commercial alloys being stronger than small laboratory melts.

It appears that the optimum alloy for general use in an HTGR for operation up to 900°C would be nickel based and contain 15% Cr, 5 to 15% Fe, 12 to 15% Co, 5 to 10% Mo or W, 2% Ti, 0.04 to 0.05% C, and 0.01 to 0.02% La. Such an alloy is not available at present.

The present study has revealed considerable information about alloys similar in composition to Inconel 617. Additional materials evaluated were Cabot alloy 214, IN-519, and two special alloys (GA 911 and GA 912). Cabot alloy 214 does not seem to have any properties that would make it useful in an HTGR system. It does not have good creep strength up to 900°C, and the weld metal is even weaker than the base metal. It ages and becomes brittle at ambient temperature, and it appears to carburize. The special alloys (GA 911 and GA 912) are strong at low and intermediate temperatures but are weaker than Inconel 617 and HD 556 at high temperatures. They appear to resist carburization. The cast alloy IN-519 was not evaluated in its normal centrifugally cast form but rather in the investment cast form. The alloy normally contains niobium, and our modification with titanium had much lower strength and ductility. The data were not conclusive concerning carburization, because the alloy contains 0.25 to 0.30% carbon in the as-cast form. The alloy appeared to have reasonably good properties for use as cast components. However, alloy 713LC has superior strength and is better established for investment casting.[7]

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