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A NICKEL-BASE ALLOY, NASA WAZ-16, WITH POTENTIAL FOR GAS TURBINE STATOR VANE APPLICATION

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16. Abstract

A nickel-base superalloy based on the nickel-aluminum-tungsten system designated WAZ-16 was developed for high strength in the 1095° C (2000° F) to 1205° C (2200° F) range. Its tensile strength at the latter temperature is approximately 186 MN/m^2 (27 000 psi). The combination of properties of the alloy suggest that it has potential as a stator vane material in advanced gas turbine engines.

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A NICKEL-BASE ALLOY, NASA WAZ-16, WITH POTENTIAL FOR GAS TURBINE STATOR VANE APPLICATION

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SUMMARY

The composition of the NASA nickel-base alloy, WAZ-20, was modified to improve its properties for potential stator vane application. The modified alloy is designated WAZ-16 and has the nominal composition in weight percent of 16 tungsten, 7 aluminum, 2 molybdenum, 2 columbium, 0.5 zirconium, 0.2 carbon, and the balance nickel.

The alloy has a tensile strength of approximately 186 MN/m^2 (27 000 psi) at 1205° C (2200° F) compared to 138 MN/m^2 (20 000 psi) for WAZ-20. Its tensile ductility, ranging from 2 to 5 percent, is almost identical with that of WAZ-20, as are its longtime stress-rupture properties. Both alloys have a 100-hour use temperature at 103 MN/m^2 (15 000 psi) of 1040° C (1900° F). At room temperature, as-cast notched impact strength is 19 joules (14 ft-lb) slightly higher than that of WAZ-20 and two to four times higher than that of typical commercial nickel- and cobalt-base alloys. In addition to these improved mechanical properties, the alloy's density was lowered to 8.75 g/cm^3 (0.316 $lb/in.^3$) as compared to 9.02 g/cm^3 (0.326 $lb/in.^3$) for WAZ-20.

INTRODUCTION

Higher temperature superalloys are required to meet the demands imposed by the higher turbine inlet-gas temperatures of newer aircraft turbine engines. The stator vanes are particularly limited by material capability because, of all the hot engine components, they are subjected to the maximum gas temperatures in the engine cycle. Conventional highly alloyed cast nickel-base alloys drop off sharply in strength above approximately 1095° C (2000° F) because the γ' phase, upon which these alloys primarily depend for high temperature strength, agglomerates or goes into solution in this temperature range (ref. 1). Cobalt-base alloys which usually have higher strength above 1095° C (2000° F) than nickel-base alloys, are therefore often used for stator vane applications.

To obtain a higher strength nickel-base alloy for use above 1095° C (2000° F) as a possible stator vane material, the nickel-tungsten-aluminum system was explored (ref. 2). This system has a higher melting point than currently used nickel-base systems. A promising alloy, WAZ-20, having a nominal composition in weight percent of 17 to 20 tungsten, 6 to 7 aluminum, 1.4 to 1.6 zirconium, 0.10 to 0.20 carbon and the balance nickel, resulted from this work (ref. 2). WAZ-20 has an incipient melting point of approximately 1300° C (2375° F) and a tensile strength of 138 MN/m^2 (20 000 psi) at 1205° C (2200° F). It has other desirable properties such as unusually high impact strength and apparent microstructural stability. An extensive microstructural study of the alloy is given in reference 3.

Because of the potential of WAZ-20 for high temperature applications such as stator vanes, further work was done to enhance its properties. Specifically, the major goals were to reduce the alloy's average density (9.02 g/cm^3 (0.326 $lb/in.^3$)) to a level below that of most commercially used stator vane alloys, and simultaneously improve its already attractive high temperature properties. Compositional modifications were made to achieve the stated goals. To reduce density the WAZ-20 alloy was modified by changing the quantity and ratio of tungsten and aluminum, and screened by means of 1205° C (2200° F) tensile tests. Castability, alloy ductility, melting point, and density were also used as criteria in selecting the most promising of these modified alloys. The alloy selected had charge weights of 17 percent tungsten and 7 percent aluminum and is identified in figure 1. This alloy was then evaluated in stress to rupture at 1095° C (2000° F). Because its stress-rupture life was lower than that of WAZ-20, additions of columbium and molybdenum were made to achieve additional strength as shown in figure 2 with the additional requirement that the 1205° C (2200° F) tensile properties would be maximized and the incipient melting point of the resulting alloys should not be less than that of WAZ-20. The strongest alloy on this basis was designated WAZ-16 and had a nominal composition in weight percent of 16 tungsten (W), 7 aluminum (Al), 2 molybdenum (Mo), 2 columbium (Cb), 0.5 zirconium (Zr), 0.2 carbon (C), and the balance nickel (Ni). WAZ-16 was then more fully evaluated by tensile, stress-rupture, and impact tests. Microstructural stability was investigated and metallographic studies were made. All studies were conducted with the alloy in the random polycrystalline form. Data comparisons are presented with high temperature, high strength nickel- and cobalt-base alloys.

MATERIALS, APPARATUS, AND PROCEDURE

Materials

The purities of the various alloying elements in weight percent as reported by the suppliers were as follows: Ni, 99.9; W, 99.9; Al, 99.88; Mo, 99.5; Cb, 99.6; and C, 99.5. Zirconium and trace amounts of other elements were picked up from the crucible during induction melting. Chemical analysis of random heats of WAZ-16 were made by an independent laboratory and are shown in table I together with the nominal composition and suggested compositional range. The analyses indicated that the compositions of the heats checked fell close to the compositional range. The single exception was the extremely low zirconium content noted in one heat. Changes in the melting procedure (elimination of the initial argon melt) compared to that used for WAZ-20 (ref. 2) result in a lower zirconium content for WAZ-16.

Melting, Casting, and Inspection Techniques

Melts were made in a 50-kilowatt, 10-kilohertz, water-cooled induction unit. In all cases castings were made directly from virgin material in a single melting procedure. Melting was done in stabilized zirconia crucibles in a vacuum of approximately 10 micrometers. Carbon and tungsten additions were made in the form of powders precharged into the cold crucible with nickel platelets and columbium roundels. Aluminum was added in the form of granules after the initial charge had melted. The melt was subsequently superheated to approximately 1650° C (3000° F) and poured at 1565° C (2850° F). Superheat and pour temperatures were determined by optical pyrometer. Zircon shell molds preheated to 870° C (1600° F) were used for casting test bars. Test bars were vapor blasted and then inspected by X-ray and fluorescent-dye penetrant techniques before testing. Only defect-free bars were tested.

Heat Treatment

The WAZ-16 alloy was given a dual exposure to determine alloy stability and resistance to embrittlement. This consisted of a high and intermediate temperature exposure in an argon atmosphere. The high temperature exposure was for 100 hours at 980° C (1800° F) and was primarily intended to determine if carbide morphology would be adversely affected. The intermediate temperature exposure was for 500 hours at 870° C (1600° F) and was meant to determine possible effects of sigma or other embrittling phases on alloy ductility.

Specimens

Test specimens all had a random polycrystalline structure. The same type of specimen was used for both tensile and stress-rupture property evaluation. Machining was not necessary for the tensile/stress-rupture bars since they were cast to final dimensions. These specimens had conical shoulders with a 20° included angle. The gage section was 3.0 cm (1.2 in.) long and 0.64 cm (0.25 in.) in diameter. Charpy impact bars were cast slightly oversize and finish-machined to obtain the 1.00- by 1.00-cm (0.394- by 0.394-in.) ASTM standard cross section dimensions.

Alloy Evaluation

Tensile and stress-rupture tests. - All tensile and stress-rupture data were obtained in air except for one stress-rupture test point which was obtained in a helium environment. The specimens were tested without protective coatings. The range of tensile test temperatures was from room temperature to 1205° C (2200° F). Tests were conducted on a hydraulically operated tensile testing machine. The average strain rates ranged from 0.001 to 0.03 cm/cm/min (0.001 to 0.03 in./in./min) and were calculated from the measured elongation after fracture and the total test time. This type of test gives comparable results to those obtained with a mechanically operated tensile testing machine (ref. 4). Stress-rupture tests were run at stresses of 28, 55, 103, and 207 MN/m^2 (4000, 8000, 15 000, and 30 000 psi) and over a temperature range of 1010° to 1205° C (1850° to 2200° F).

Impact tests. - A standard Charpy impact tester was used to measure impact strength at room temperature. V-notched (ASTM Type A) specimens were tested in both the as-cast and aged conditions. Oversize cast bars were exposed for 100 hours at 980° C (1800° F) followed by 500 hours at 870° C (1600° F), machined to standard impact specimen dimensions, and tested at room temperature.

Hardness. - Hardness readings were taken on flat ground as-cast surfaces. Bars that had been heat treated were subsequently ground and tested in a similar manner. Both Rockwell "A" and "C" hardness scale tests were run. Five tests for each scale were obtained as a measure of average material hardness.

Metallography. - Photomicrographs of WAZ-16 are provided in the as-cast and aged condition. The etchant used to obtain the photomicrographs was 92 parts by volume HCL, 3 HNO_3, and 5 H_2SO_4. The incipient melting temperature was determined by exposing samples cut from cast tensile bars for 1/2 hour at various temperatures from 1260° to 1345° C (2300° to 2450° F) in a heat treating furnace.

Density. - Several as-cast WAZ-16 tensile/stress-rupture specimens were used to measure density by displacement of water.

RESULTS AND DISCUSSION

Tensile Properties

All tensile data are listed in table II. Figure 3 shows the ultimate tensile strength and the elongation of WAZ-16 as a function of temperature from room temperature to 1205° C (2200° F). As is common with many nickel-base alloys the maximum strength does not occur at room temperature but rather at an intermediate temperature. In this case the maximum strength of 751 MN/m^2 (109 000 psi) occurred at 760° C (1400° F), whereas room temperature strength is 634 MN/m^2 (92 000 psi). Elongation at room temperature averaged 4.5 percent. In the intermediate temperature range from 650° to 982° C (1200° to 1800° F) elongation remained relatively constant between 2 and 3 percent. Maximum elongation was 5 percent and occurred at 1095° C (2000° F) and above.

Figure 4 compares the tensile properties of WAZ-16 and WAZ-20 (ref. 2) at high temperatures, between 980° and 1205° C (1800° and 2200° F), the range of primary interest for this alloy for turbine engine stator vanes. WAZ-16 begins to show higher tensile strength than WAZ-20 between 980° and 1095° C (1800° and 2000° F). At 1205° C (2200° F) its strength is 186 MN/m^2 (27 000 psi) compared to 138 MN/m^2 (20 000 psi) for WAZ-20. Tensile ductility is about the same as that of WAZ-20, ranging from 2 percent at 980° C (1800° F) to 5 percent at 1205° C (2200° F).

Since stator vanes of advanced engines may be expected to operate up to temperatures approximating 1205° C (2200° F), tensile strength comparisons of nickel- and cobalt-base alloys that may be considered for stator vanes are in order at such a high temperature. Available mechanical property data for superalloys are limited at this temperature. However, a comparison is provided in figure 5 with the nickel-base alloys WAZ-20 (ref. 2), TAZ-8A (ref. 4), and TAZ-8B (ref. 5), the cobalt-base alloy VM-108 (ref. 6), and TD-NiCr (refs. 7, 8, and 9), a dispersion strengthened alloy currently under consideration for advanced stator vane applications. As might be expected, because of the higher melting point of cobalt as compared to nickel, the cobalt-base alloy is stronger (based on extrapolation of the data from ref. 6) at this high temperature than the relatively conventional γ'-strengthened nickel-base alloys TAZ-8A and TAZ-8B. But it has less than half the strength of WAZ-16, 83 MN/m^2 (12 000 psi) as against 186 MN/m^2 (27 000 psi). Processing variations result in a wide range of reported properties for TD-NiCr. Both bar and sheet data are included. WAZ-16 however has a 50 percent higher tensile strength than the maximum reported value for TD-NiCr.

Stress-Rupture Properties

Stress-rupture data are tabulated in table III and plotted in figure 6. Open symbols represent air data, and the single closed symbol on the plot is a helium atmosphere test point. Rupture lives ranged from 2200 hours at 1095° C (2000° F) and 28 MN/m^2 (4000 psi) to 1.6 hours at 1065° C (1950° F) and 207 MN/m^2 (30 000 psi). Isostress lines are shown for the range of test temperature and stresses investigated. Doubling the stress reduced life by approximately an order of magnitude. Although only a single test point was obtained in helium, an improvement in stress-rupture life was obtained. This suggests that suitable coatings could significantly extend the alloy's rupture life by providing protection against oxidation.

Figure 7 compares the 103 MN/m^2 (15 000 psi) isostress curves of WAZ-16 and WAZ-20 over a temperature range from 1010° to 1150° C (1850° to 2100° F). It is apparent that the alloying modifications made in WAZ-16 did not adversely affect these stress-rupture properties in this stress and temperature region of particular interest. The curves are virtually identical for both materials.

Available stress-rupture data for nickel- and cobalt-base alloys at very high temperatures are also extremely limited. However, it was possible in figure 8 to make a comparison of WAZ-16 and a typical conventional γ'-strengthened alloy TAZ-8A (ref. 4), the strong high temperature cobalt-base alloys VM-108 and MAR-M 322 (ref. 6), as well as TD-NiCr (refs. 7, 8, and 9) at a temperature and stress combination of interest for advanced stator vane applications, 55 MN/m^2 (8000 psi) and 1165° C (2125° F). The nickel alloy data were obtained in air, whereas the data for one of the cobalt alloys, VM-108, were obtained in helium. WAZ-16 has almost three times the life of TAZ-8A at this test condition (34 hr compared to 13 hr) but only about two-thirds that of VM-108 (50 hr). However, as noted, it must be remembered that the VM-108 cobalt alloy data were obtained in an inert atmosphere (ref. 6) which is a contributory factor in achieving this high life. WAZ-16 also has approximately eight times the life of MAR-M 322, another high strength cobalt-base alloy, but one that was tested in air. Thus, at this high temperature and stress combination which may be expected in advanced engine stator vane applications, WAZ-16 has a significant life advantage over some of the strongest known cast nickel- and cobalt-base alloys. In comparison to TD-NiCr, the dispersion strengthened alloy, WAZ-16 also performs favorably. It is apparent from the reported range of rupture life that processing variables have a marked effect upon the stress-rupture properties of TD-NiCr. The projected average rupture life of WAZ-16 (34 hr) is near the center of the projected life range (8 to 70 hr) for TD-NiCr at 55 MN/m^2 (8000 psi) and 1165° C (2125° F).

In view of the considerable interest in TD-NiCr as a potential advanced stator vane material, the stress-rupture life of WAZ-16 is compared solely with this dispersion strengthened alloy in figure 9. The comparison is made over the entire range of temperatures for which data are available, 1095° to 1205° C (2000° to 2200° F) at a stress of 55 MN/m^2 (8000 psi), one which is certainly representative of the stresses contemplated for advanced engine stator vanes in the immediate future. It is interesting that over this temperature range the isostress line for WAZ-16 lies approximately in the midrange between the upper and lower limits posed by the TD-NiCr isostress band constructed from data obtained from references 7, 8, and 9. To make this comparison it was necessary to include data from sheet and bar stock and a number of processing variations in TD-NiCr.

Impact Strength

The notched Charpy impact data for WAZ-16, WAZ-20, and typical cast commercial nickel- and cobalt-base alloys are presented in table IV. When compared in the as-cast condition, WAZ-16 has the highest impact resistance (19 J or 14 ft-lb) of the four materials. WAZ-20 is somewhat less impact resistant in the as-cast condition but slightly more impact resistant in the aged conditions. Aging had no measurable effect on impact resistance of the WAZ-16 alloy. Typical impact resistance data for commercial cobalt- and nickel-base alloys used today for aircraft turbine engine stator vanes is substantially lower, 3 to 6 joules (2 to 4 ft-lb) and 8 to 11 joules (6 to 8 ft-lb), respectively.

Hardness

Hardness data in both Rockwell "A" and "C" ranges are presented in table V. WAZ-16 and WAZ-20 have similar hardness in both the as-cast and aged conditions. Aging may have slightly reduced the hardness of WAZ-16 (66.6 to 64.7 Rockwell "A").

Density

The reduced tungsten content together with the small increase in aluminum content as compared to WAZ-20 resulted in a 3 percent decrease in density for WAZ-16. The measured values averaged 8.75 g/cm^3 (0.316 $lb/in.^3$) and ranged from 8.72 to 8.78 g/cm^3 (0.315 to 0.317 $lb/in.^3$). This density is substantially lower than that of most currently available advanced temperature cobalt-base stator vane alloys. Compared to most other cast nickel-base alloys, its density is still somewhat high.

Incipient Melting Temperature

Metallographic examination of cast tensile bars heated for 1/2-hour at various temperatures revealed that incipient melting was evident after 1300° C (2375° F) exposure and not after 1290° C (2350° F) exposure. Other nickel-base alloys have substantially lower incipient melting temperatures, usually on the order of 1205° C (2200° F).

Metallography

Micrographs of WAZ-16, in the as-cast condition are shown in figure 10(a) at magnifications of 250 and 750. Large primary γ' type nodules are in evidence. Some carbides are present. Grain boundaries are not distinguishable.

The effect of exposure for 100 hours at 980° C (1800° F) plus 500 hours at 870° C (1600° F) on the microstructure is shown in figure 9(b) at magnifications of 250 and 750. Carbide morphology was not adversely affected. Additional precipitation appears to have occurred, however, and the phases are more sharply defined. There is no evidence of any acicular embrittling phase having been formed.

CONCLUDING REMARKS

Although only limited data have been obtained for NASA WAZ-16, the alloy appears to have considerable potential for high temperature stator vane applications. Strength comparisons at high temperature show it to be superior to known cast alloys, both nickel and cobalt base, in the temperature range of interest. Its impact resistance is substantially higher than such alloys and its incipient melting temperature is substantially higher than that of conventional cast nickel-base alloys. There is no evidence of formation of embrittling phases after longtime exposure and the alloy would appear to have decided advantages over its predecessor, WAZ-20.

The stress-rupture strength of WAZ-16 is certainly comparable to that of TD-NiCr up to 1205° C (2200° F) at a stress level of interest for advanced turbine engine stator vanes. Although the density of WAZ-16 is somewhat higher, 8.75 g/cm^3 (0.316 lb/in.^{3}) compared to 8.48 g/cm^3 (0.306 lb/in.^{3}), this may not be a prime consideration in stationary components such as stator vanes, certainly not for ground based power systems. From the point of view of the cost of making a finished part, the relative ease of casting to a final blade shape which is possible with WAZ-16 compared to the rather elaborate processing required for TD-NiCr, there would appear to be a distinct advantage with WAZ-16. From this same cost standpoint, remelt material recovery which is possible with WAZ-16, would also afford an advantage.

Of course to effectively utilize this alloy, suitable protective coatings must be developed. The substrate is not subject to catastrophic oxidation at high temperatures and provision of a suitable coating does not appear to be an insurmountable problem. Taken as a whole NASA WAZ-16 is an alloy that affords interesting opportunities for advanced engine stator vanes applications and merits further consideration and investigation.

SUMMARY OF RESULTS

The following results were obtained from an investigation to improve the properties of the NASA WAZ-20 nickel-base alloy for potential application to stator vanes of advanced gas turbine engines:

1. A new alloy based upon the WAZ-20 chemistry was developed. It is designated WAZ-16 and its nominal composition in weight percent is 16 tungsten, 7 aluminum, 2 molybdenum, 2 columbium, 0.5 zirconium, 0.2 carbon, and the balance of nickel.

2. The alloy has substantially higher tensile strength in the 1095° to 1205° C (2000° to 2200° F) range than WAZ-20. At the latter temperature its ultimate tensile strength was 186 MN/m^2 (27 000 psi) compared to 138 MN/m^2 (20 000 psi). Tensile ductility ranged from a minimum of 2 percent at 980° C (1800° F) to 5 percent at 1205° C (2200° F), essentially no different from that of WAZ-20.

3. The alloy's long time stress-rupture properties are virtually identical to those of WAZ-20. At 1010° C (1850° F) and 103 MN/m^2 (15 000 psi) the average rupture life was 177 hours, and at 55 MN/m^2 (8000 psi) and 1205° C (2200° F) it was 9.2 hours.

4. WAZ-16 has a lower density than WAZ-20: 8.75 g/cm^3 (0.316 $lb/in.^3$) compared to 9.02 g/cm^3 (0.326 $lb/in.^3$).

5. WAZ-16 has excellent room temperature impact strength both as-cast and after aging. Average Charpy notched impact strengths in each condition were 19 joules (14 ft-lb). This compares to 14 and 23 joules (10 and 17 ft-lb) for WAZ-20 in the cast and aged conditions, respectively. Compared to typical cast commercial nickel- and cobalt-base alloys the impact strength of WAZ-16 is two to four times as great.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 3, 1974,
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TABLE I. - CHEMICAL ANALYSES OF WAZ-16 RANDOM HEATS

Composition, wt. %								
W	Al	Mo	Cb	Zr	C	Si	B	Ni
[a]16	[a]7	[a]2	[a]2	[a]0.5	[a]0.2	--	--	Bal[a]
[b]15 to 17	[b]6.8 to 7.2	[b]1.8 to 2.2	[b]1.8 to 2.2	[b].4 to .6	[b].15 to .20	--	--	Bal[b]
16.67	6.87	2.05	2.05	.58	.18	0.07	<5 ppm	Bal
16.56	6.97	2.40	1.94	.09	.19	.06	<5 ppm	Bal
15.80	7.04	2.18	2.01	.46	.17	.06	<5 ppm	Bal

[a]Nominal composition.
[b]Suggested compositional range.

TABLE II. - TENSILE DATA

Alloy	Temperature		Ultimate tensile strength		Elongation, percent
	^{o}C	^{o}F	MN/m^2	psi	
Ni-13W-6Al	1205	2200	52	7 500	65
Ni-15W-6Al	1205	2200	71	10 300	38
Ni-17W-6Al	1205	2200	106 104	15 400 15 100	23 22
Ni-13W-7Al	1205	2200	99	14 300	32
Ni-15W-7Al	1205	2200	121	17 600	22
Ni-17W-7Al	1205	2200	146	21 200	25
Ni-15W-8Al	1205	2200	161	23 400	7
WAZ-16	20	70	620 655	89 600 94 700	5 4
	650	1200	720	104 000	$2\frac{1}{2}$
	760	1400	750	108 500	3
	870	1600	460 530	66 500 77 000	2 $2\frac{1}{2}$
	980	1800	355 435	51 500 63 000	$2\frac{1}{2}$ 2
	1095	2000	310 370	45 300 53 500	5 5
	1205	2200	185 185	26 500 26 700	5 5

TABLE III. - STRESS-RUPTURE DATA

Alloy	Test temperature		Stress		Life hr
	^{o}C	^{o}F	MN/m^2	psi	
Ni-17W-7Al	1095	2000	103	15 000	6.8 10.9
Ni-17W-7Al-1Cb	1095	2000	103	15 000	7.5 12.4
Ni-17W-7Al-2Cb	1095	2000	103	15 000	16.6
WAZ-16	1010	1850	103	15 000	186.7 200.0 160.0 163.4
			207	30 000	9.7
	1040	1900	103	15 000	79.5 77.0 95.8 81.6 69.4
	1065	1950	103	15 000	47.1 31.5
			207	30 000	1.6
	1095	2000	28	4 000	2242.2
			55	8 000	233.5 275.0
			103	15 000	16.4 14.2 16.2
	1120	2050	103	15 000	8.6 12.6 6.6
	1150	2100	28	4 000	421.0
			55	8 000	52.9
			103	15 000	2.0 2.4 3.1
	1205	2200	28	4 000	63.1
			55	8 000	20.8 (helium) 7.8 5.7 12.6

TABLE IV. - NOTCHED CHARPY IMPACT STRENGTH OF SEVERAL ALLOYS AT ROOM TEMPERATURE

Alloy	Condition	Impact resistance	
		J	ft-lb
WAZ-16	As cast	19	14
	Exposed[a]	18	13
WAZ-20	As cast (from ref. 2)	14	10
	Exposed[a]	23	17
	Exposed (from ref. 2)[b]	22	16
Typical nickel-base (commercial)	As cast	8 to 11	6 to 8
Typical cobalt-base (commercial)	As cast	3 to 6	2 to 4

[a]100 hr at 980° C (1800° F) + 500 hr at 870° C (1600° F).
[b]1000 hr at 870° C (1600° F).

TABLE V. - HARDNESS DATA

Alloy	Condition	Rockwell "A"		Rockwell "C"	
		Range	Average	Range	Average
WAZ-16	As cast	66.4 to 66.8	66.6	31 to 34	32.4
	Exposed[a]	63.8 to 65.4	64.7	31 to 32	31.6
WAZ-20	As cast (from ref. 2)	66.7 to 67.8	67.5	--	--
	Exposed (ref. 2)[b]	67.0 to 67.8	67.4	--	--
	Exposed[a]	66.2 to 66.7	66.5	31 to 32	31.8

[a]100 hr at 920° C (1800° F) + 500 hr at 870° C (1600° F).
[b]1000 hr at 870° C (1600° F).

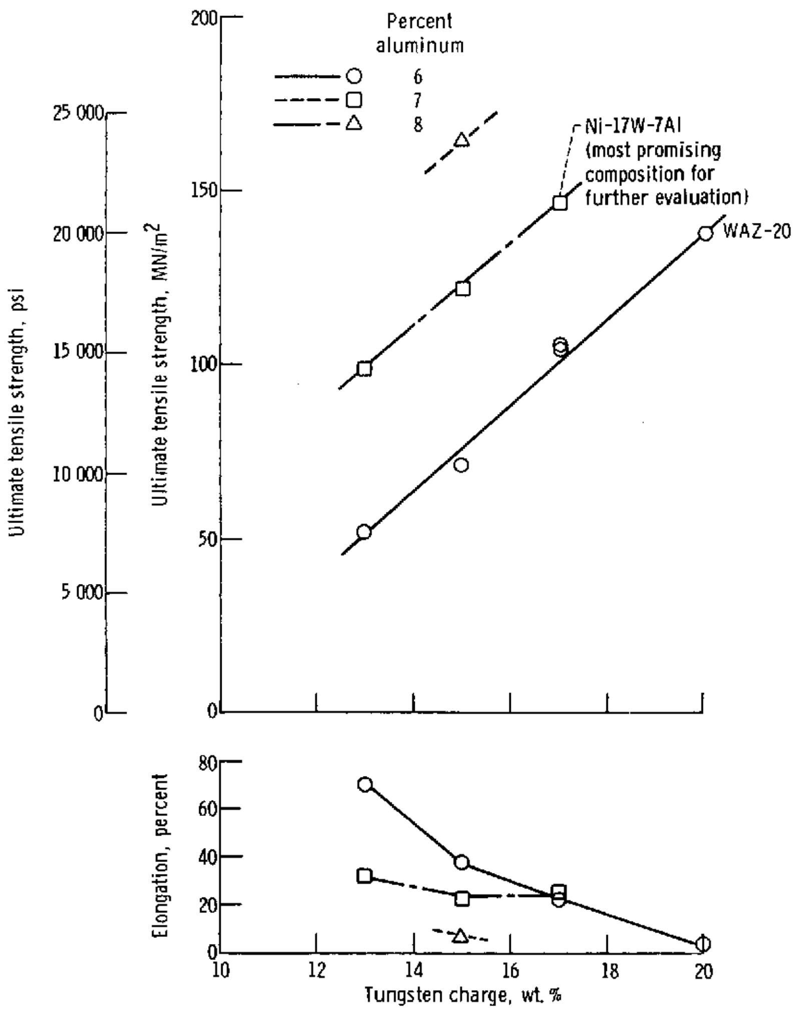


Figure 1. - Tungsten-aluminum-zirconium modified nickel-base alloys screened for 1205° C (2200° F) tensile properties.

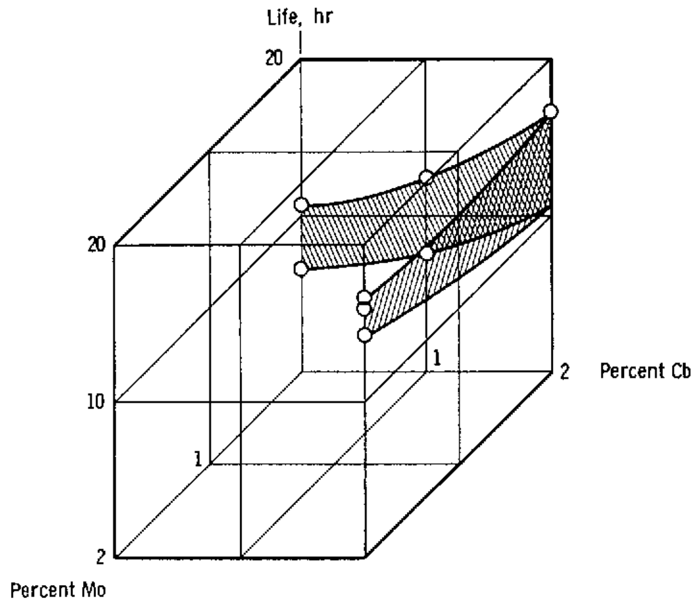


Figure 2. - Effect of alloying additions on stress-rupture life of Ni-17W-7Al alloy at 1095° C (2000° F) and 103 MN/m^2 (15 000 psi). (See fig. 1 and table III.)

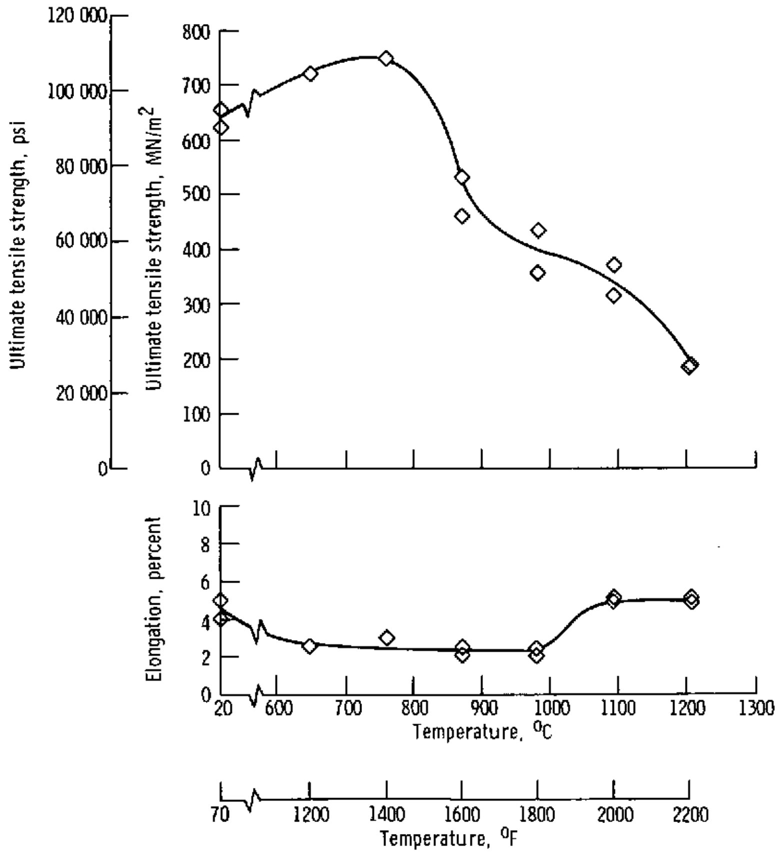


Figure 3. - Tensile properties of WAZ-16.

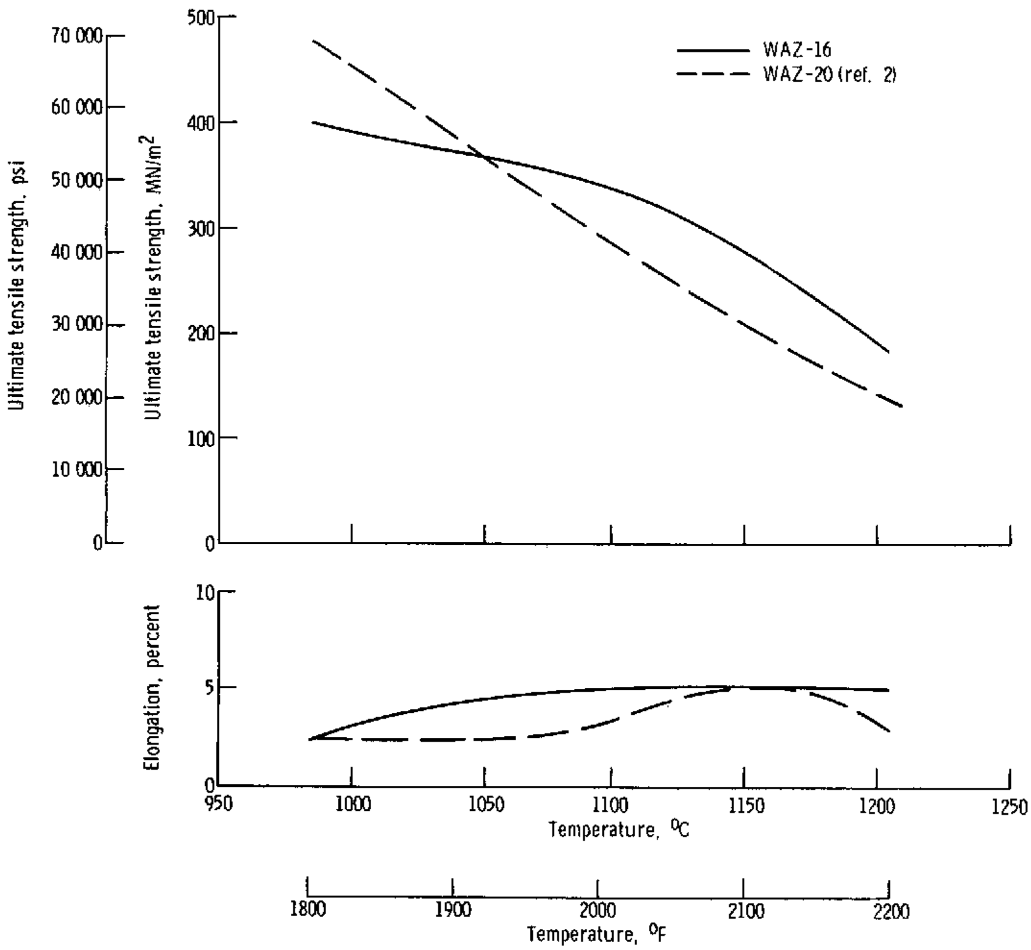


Figure 4. - Comparison of tensile properties of WAZ-16 and WAZ-20.

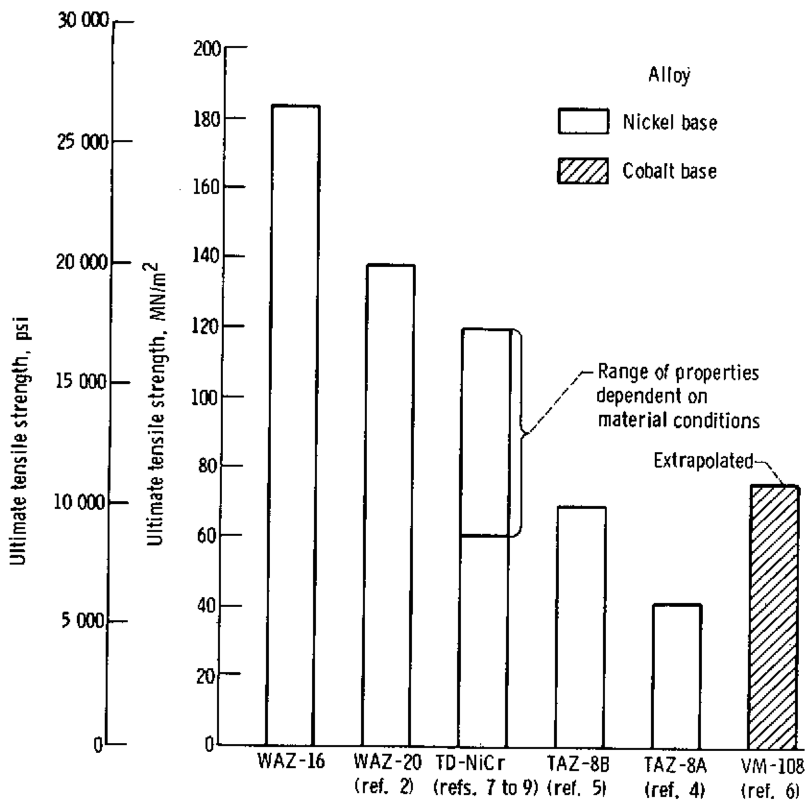


Figure 5. - Ultimate tensile strengths of selected nickel- and cobalt-base alloys at 1205° C (2200° F).

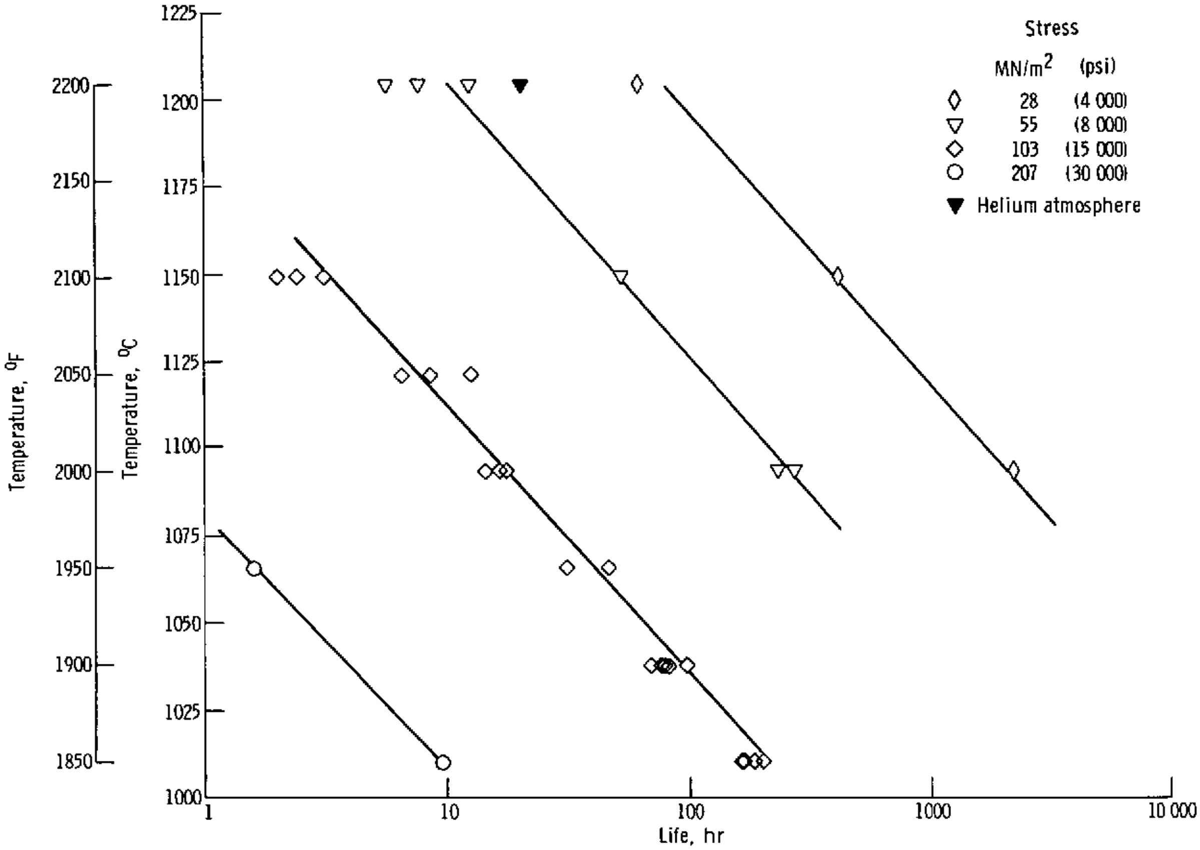


Figure 6. - Stress-rupture properties of WAZ-16.

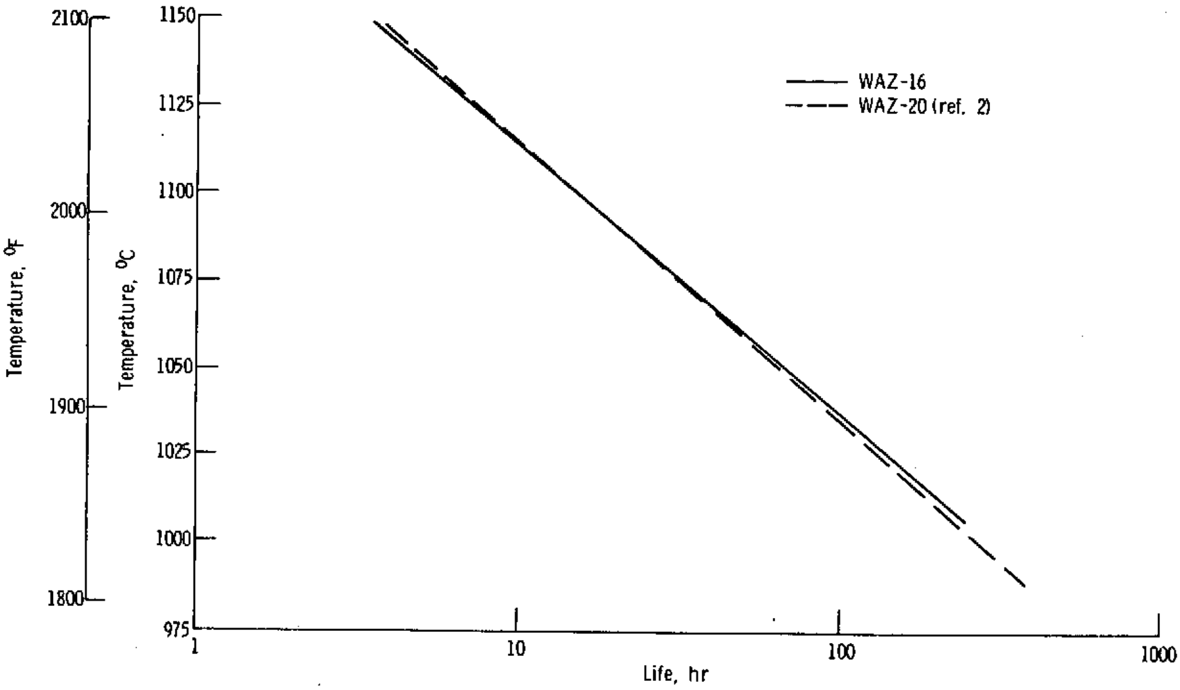


Figure 7. - Stress-rupture properties of WAZ-16 and WAZ-20 in random polycrystalline form at 103 MN/m^2 (15 000 psi).

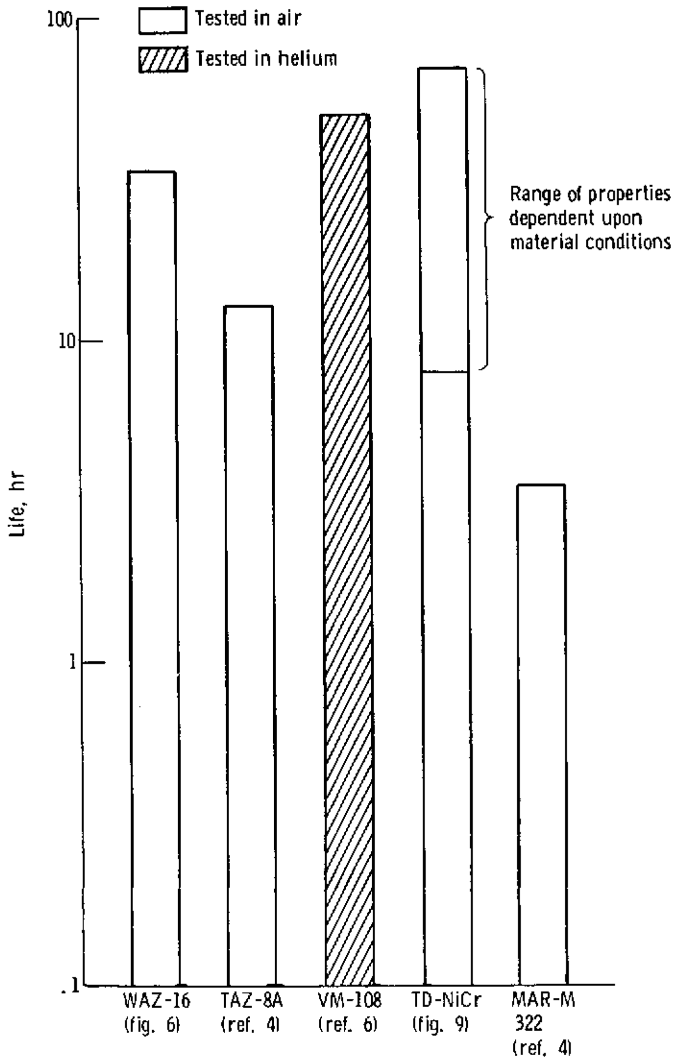


Figure 8. - Stress-rupture life comparison of WAZ-16 and selected nickel- and cobalt-base alloys at 1165^{0} C (2125^{0} F) and 55 MN/m^{2} (8000 psi).

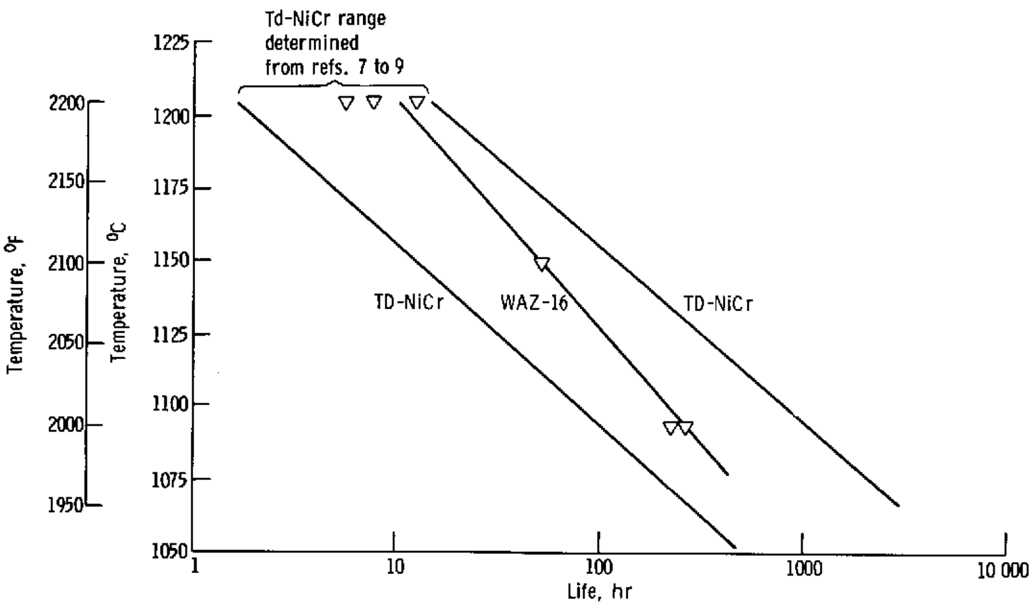
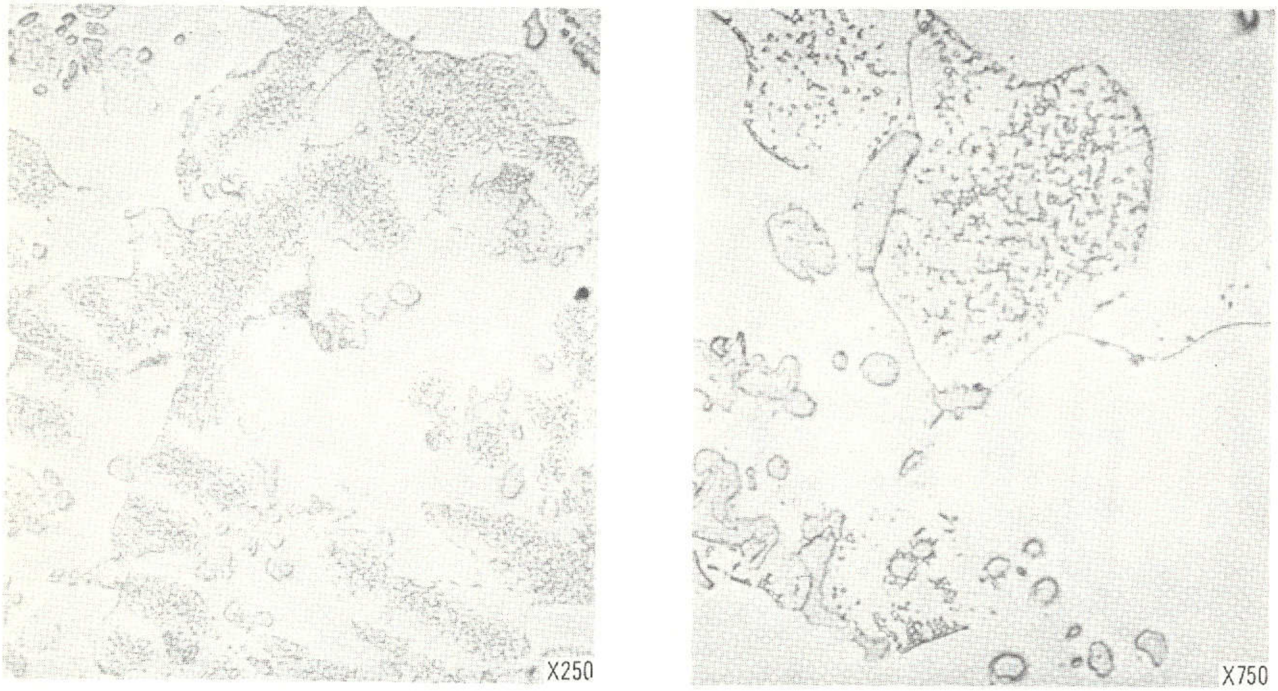
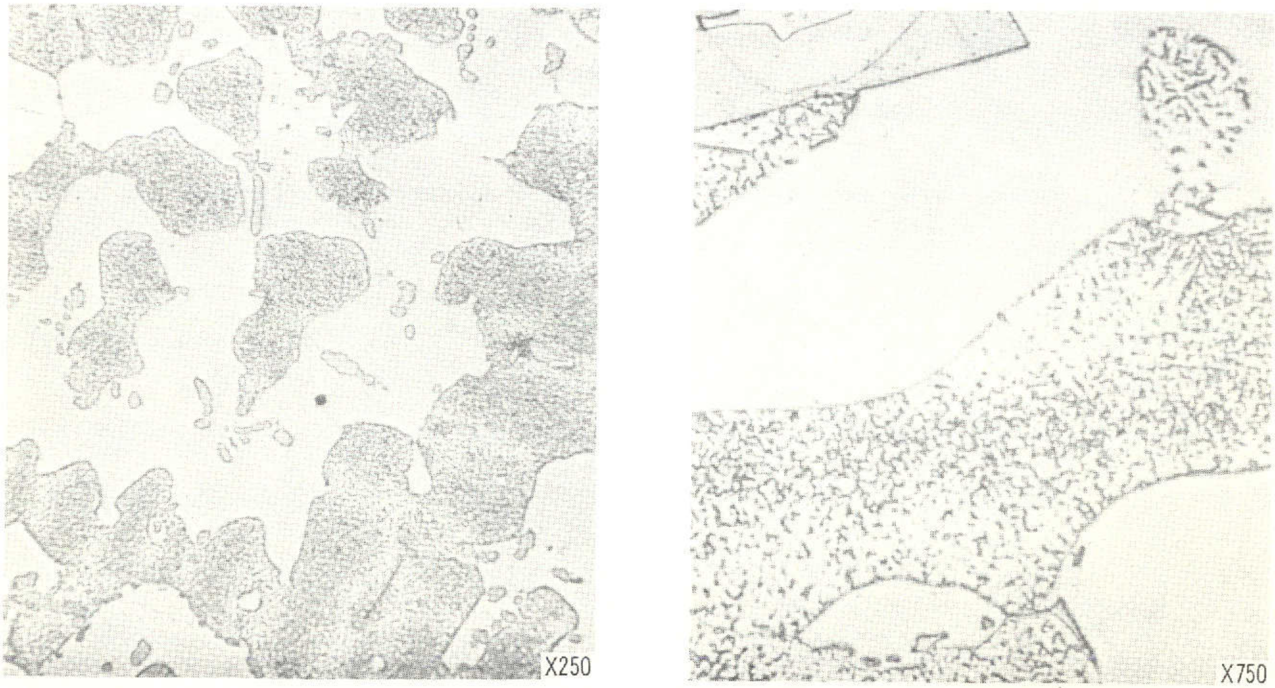


Figure 9. - Isostress comparison of stress-rupture life of WAZ-16 and TD-NiCr at 55 MN/m^2 (8000 psi).



(a) As-cast.



(b) Aged 100 hr at 982° C (1800° F) plus 500 hr at 871° C (1600° F).

Figure 10. - Microstructure of WAZ-16.

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