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TECHNICAL PAPER proposed for presentation at Spring Conference of the Gas Turbine Division of the American Society of Mechanical Engineers
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ABSTRACT

A high strength nickel base alloy has been developed which compares favorably in oxidation resistance with known high strength nickel base alloys. The alloy, although basically a cast material, also possesses workability potential.

After 310 hours exposure to air at 1900° F, the alloy had a weight gain of 1.8 mg/cm^2. The total affected zone, external oxide scale plus depletion zone, was 0.4 mil. This compares with a weight gain of 3.0 mg/cm^2 and a total affected zone depth of 3.3 mils for René 41 after only 100 hours exposure at 1900° F. In sheet form after 8 hours at 2200° F, its oxidation resistance was approximately the same as that of René 41 at 1900° F.

Tensile strengths of the alloy after rolling and heat treatment ranged from an average of 185,000 psi at 1400° F to 3000 psi at 2200° F. Maximum elongation was 55 percent and occurred at the latter temperature. At 1900° F, average tensile strength was 64,500 psi in the as-cast condition, and 54,000 psi after rolling and heat treatment.

Stress rupture data for low and intermediate stress levels were obtained. In the as-cast condition, use temperatures for 500, 100, and 10 hour life at 15,000 psi are 1815°, 1895°, and 2010° F, respectively. At 8000 psi and 2125° F

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rupture life was 13 hours and compared favorably with some of the strongest known nickel and cobalt base alloys.

The very good high temperature oxidation resistance, good high temperature strength, and at least limited workability of this alloy suggest that it may be applicable for use in advanced gas turbine engine components.

INTRODUCTION

Nickel base alloys have potential for meeting the materials requirements of many aerospace applications in an intermediate temperature range from approximately 1500° to 2200° F. Turbojet engine components such as stator vanes, turbine buckets, transition ducts, and afterburner liners are among the most important applications for such alloys. For these uses alloys should have the best possible oxidation resistance. Although protective coatings will probably be required to permit longtime (thousands of hours) operation at temperatures above 1800° F, the best possible oxidation resistance is desirable, both in lieu of the development of satisfactory coatings and to minimize the damage if coatings are chipped or spalled during engine operation. Research is underway at the Lewis Research Center to provide nickel base alloys with improved high temperature oxidation resistance and adequate high temperature strength capability for gas turbine and other elevated temperature applications.

Earlier research at the NASA Lewis Research Center has led to the development of a series of high strength cast nickel base alloys (refs. 1 to 6). The strongest of these, TAZ-8, is comparable in high temperature tensile and stress rupture strength with the stronger commercial cast nickel base alloys such as MAR-M200 and IN-100, although its oxidation resistance is somewhat less. The nominal composition of TAZ-8 in weight percent is 8 tantalum, 6 chromium, 6 aluminum, 4 molybdenum, 4 tungsten, 2.5 vanadium, 1 zirconium, 0.125 carbon, and the balance nickel. Basically a cast alloy, TAZ-8 has also been successfully fabricated into bar and sheet. For example, thickness reductions of 50 percent were obtained with 1/2-inch diameter as-cast bars by unidirectional forging techniques at room temperature (ref. 5). Cast sheets of this alloy approximately 0.100 inch thick were rolled to 0.015 inch by specialized techniques (ref. 7). Such workability potential is beneficial in that it broadens the applicability of the alloy. In view of the interesting properties of TAZ-8 it was believed that the desired goal of an alloy with improved oxidation resistance together with high temperature strength as well as workability potential could be achieved by modifying the TAZ-8 composition.

Consideration of the composition of TAZ-8 suggested that of the elements present vanadium was most likely to adversely affect its oxidation resistance. Vanadium forms several oxides. One of these, V_2O_5, melts at 675° C and is relatively volatile. Another investigator (ref. 8) has shown that an iron-nickel-chromium alloy when heated in contact with this oxide experienced catastrophic oxidation in still air at 900° C. Since vanadium has been shown to be a major strengthener (ref. 2) in this alloy system, additional strengtheners would be required if vanadium were removed an alloying study was therefore conducted in which vanadium was removed from the TAZ-8 alloy and systematic additions of columbium were made. Columbium is known to form carbides and to combine with nickel to form a relatively high melting point intermetallic compound Ni_3Cb (ref. 9). A small quantity of boron (0.004 percent) was also added to all of the alloys investigated. Boron in small amounts has been shown to have beneficial effects on stress rupture life and hot workability of some nickel base alloys (ref. 10). A composition, referred to as TAZ-8A, which afforded a good balance between improved oxidation resistance and high temperature strength was then selected for extensive mechanical and physical property data determinations. Oxidation data were obtained from 1900° to 2200° F. Rollability was investigated and tensile data were obtained in the as-cast and sheet form up to 2200° F. Stress rupture data were obtained up to 2125° F. Comparisons with representative cast and wrought alloys are presented.

EXPERIMENTAL PROCEDURE

Alloys Investigated

The strongest previously developed alloy in this series, TAZ-8, was modified by removing vanadium and making systematic additions of columbium. A constant small amount of boron (0.004 percent) was also added to each alloy. The nominal compositions of the alloys investigated are given in table I.

Purity of raw materials. - The purities of the alloying elements used, as reported by the suppliers, are listed in table II.

Chemical analysis. - Chemical analyses of randomly selected heats of TAZ-8A, the alloy selected for more extensive evaluation, were made by an independent laboratory and are also shown in table I. In general, these analyses indicated that the compositions of the various heats were close to the nominal composition.

Casting and Inspection Techniques

Melts were made in 50-kW, 10,000 cycle per second, water-cooled induction units. When melting under an inert gas (commercially pure argon) cover, the procedure was similar to that described in references 1 to 3. Stabilized zirconia crucibles were used and the pouring temperature, as determined by an optical pyrometer, was $3050 \pm 50^{\circ}$ F. The melts were poured without argon protection into silica molds preheated to 1600° F. Castings were allowed to air cool to room temperature before the investment was removed. When melts were made under vacuum the pourint temperature, as determined by an optical pyrometer, was 3100 ± 50° F. Melts were poured into zircon shell molds preheated to 1600° F. A pressure of 10 microns or less was maintained during melting and pouring.

Stress rupture and tensile bars were cast to final dimensions. The same type of specimen was used for both stress-rupture and tensile tests of as-cast material. These specimens had conical shoulders with a 20-degree included angle. The gage section was 1.20-inch long and 0.25 inch in diameter. Charpy impact bars were cast slightly oversize and finish machined to standard dimensions. Blanks for rolling studies were cast to dimensions of 3X1.5X0.11 inches.

All cast test specimens as well as rolled sheet strips were vapor blasted prior to inspection. Prior to testing, all specimens were inspected by X-ray and by fluorescent-dye penetrant techniques.

Rolling

Cast blanks of TAZ-8A were cut into three sections 3X0.5X0.11 inches. Each section was rolled into sheet strips approximately 0.020-inch thick. The blanks were unidirectionally rolled at 1900° F in a conventional 4-high mill at a surface speed of 80 feet per minute. Reductions of 0.001 inch per pass, approximately 1 percent of the original thickness, were employed. Tensile specimens having a test section 1-inch long by 0.175 by 0.020 inch were machined from these rolled strips.

Alloy Evaluation

Oxidation. - A 20 cubic foot resistance-wound, hearth-type furnace was used to determine oxidation behavior of selected alloys. Two types of oxidation specimens were used. As-cast material was machined to obtain cylinders of 0.225-inch diameter by 0.875-inch length. Rolled sheet approximately 0.020-inch thick was cut to provide segments 0.75 by 0.60 inch. The specimens were supported in individual Vycor containers by platinum wires spot welded to one end. The weight gain, including that of any spalled oxide, was first determined per unit of original surface area for each specimen. Oxidized specimens were then cleaned of surface oxide by microsandblasting and weight loss was determined by subtracting from the original weight.

Stress-rupture and tensile tests. - All stress rupture data were obtained in air. The alloys were tested in the as-cast condition without protective coatings. All tensile tests were run in air. Sheet specimens were tested in the as-rolled and in a heat-treated condition. The heat treatment consisted of a 1/2 hour anneal at 2000° F in argon, followed by a 24 hour aging treatment at 1300° F, and an air cool to room temperature.

Hardness. - Rockwell A hardness readings were taken along the test sections of as-cast stress rupture bars. An average of five readings was taken as representative of the hardness of each specimen.

Impact tests. - A standard Charpy impact tester was used to measure impact resistance at room temperature. Specimens were ground from oversize investment blanks to 0.395×0.395×2.25 inches and were unnotched.

Metallographic studies. - Metallographic studies were made of selected alloys in the as-cast condition. Photomicrographs are presented for TAZ-8A in the as-cast, as-rolled, and heat-treated conditions. Photomicrographs of TAZ-8A and representative nickel base alloys after oxidation tests are also shown and the results of a microprobe analysis of TAZ-8A after oxidation testing are presented.

EFFECTS OF ALTERING COMPOSITION OF TAZ-8 ALLOY

Oxidation Resistance

The relative effects of both columbium and vanadium on oxidation resistance are compared in figure 1 by using a modified TAZ-8 alloy (the TAZ-8 composition with zero vanadium) as a base. A marked improvement in oxidation resistance is evident upon removal of vanadium from the TAZ-8 alloy on the basis of both weight gain and weight loss tests. Columbium was not nearly as detrimental to oxidation resistance as vanadium. On a weight gain basis the oxidation resistance was not markedly changed by columbium additions up to 5 percent over that of the base line (zero-vanadium) alloy. When measured on the basis of weight loss, an observable adverse effect due to increasing columbium content occurred.

Stress Rupture

The stress-rupture capability of the columbium modified alloys at 2000° F and 15,000 pounds per square inch is shown in figure 2. Maximum stress rupture life was obtained with a 2.5 percent columbium content alloy. Average life was increased from 4 to 14 hours as columbium content was increased from 0 to 2.5 percent. Beyond this percentage of columbium rupture life generally decreased, reaching lives of less than 1 hour at columbium contents of 7.5 percent and above.

PROPERTIES OF TAZ-8A

The 2.5 percent columbium modified alloy, TAZ-8A, was selected for more thorough study. This alloy had vastly improved oxidation resistance over TAZ-8. Although its oxidation resistance was not markedly different from that of the other columbium modified alloys, it performed most favorably in stress rupture at 2000° F and 15,000 pounds per square inch. TAZ-8A (measured density 8.65

gm/cm) was therefore further evaluated and extensively compared with other alloys.

Oxidation Resistance

Oxidation specimens of representative commercial alloys supplied by the manufacturers were tested concurrently with TAZ-8A. Its 1900° F oxidation resistance in the as-cast condition is compared in figure 3 with that of three of the strongest known cast nickel-base alloys, MAR M-200, IN 100, TAZ-8, and a representative wrought alloy, René 41. On a weight gain basis only MAR M-200 shows an overall improved oxidation resistance over that of argon-melted TAZ-8A. In the vacuum-melted condition TAZ-8A compared favorably with all the other alloys up to 310 hours, the maximum test time considered, although the slope of its weight-gain curve is somewhat steeper than that of MAR M-200. On the basis of weight loss, the argon-melted TAZ-8A has generally the same oxidation resistance as the other cast alloys, although the steeper slope of its weight-loss curve suggests poorer oxidation resistance at exposure times over 100 hours. Vacuum melted TAZ-8A, however, showed substantial improvement over all the other alloys; about an order of magnitude improvement over René 41 and about a threefold improvement over the other cast alloys of all test times (fig. 3(b)).

Figure 4 shows the oxidation resistance of argon-melted TAZ-8A 0.0215-inch sheet compared with that of 0.016-inch René 41 sheet after exposure for 8 hours at various temperatures. On the basis of weight gain per unit area (fig. 4(a)), TAZ-8A sheet has approximately the same degree of oxidation resistance at 2200° F as does René 41 at 1900° F. This difference in oxidation resistance is not as marked when the comparison is made on the basis of weight loss per unit area (fig. 4(b)).

Oxidation data for Hastelloy X, long considered one of the most oxidation resistant nickel base alloys, are reported in reference 11. In the latter investigation, Hastelloy X sheet was tested at several temperatures. Weight-gain data were reported for various exposure times. The eight-hour data at 1900°, 2000°, and 2200° F may be compared with similar data for TAZ-8A sheet (argon cast). For these conditions Hastelloy X is not superior to TAZ-8A. Of course, it should be emphasized that differences in experimental procedures and techniques can introduce a degree of uncertainty in comparisons of this type.

Although oxidation resistance was determined by weight-gain and weight-loss measurements, neither measurement provides a wholly satisfactory picture of oxidation resistance. Microstructural studies of oxidized specimens and an electron microprobe analysis were therefore employed to supplement the weight-gain and weight-loss data. A disadvantage of the weight-gain data is that evaporative losses of alloying constituents are not measured. A test in which weight loss is determined is subject to error of another type, even though any evaporative losses are included in total weight loss. This error stems from the possible loss of some unoxidized metal during the cleaning process. The amount of base metal removed during cleaning was established by sandblasting an unoxidized specimen in a manner similar to that used for the oxidized samples, so that a surface texture comparable to that of cleaned oxidized specimens was obtained. The weight loss per unit area in this case was 0.3 milligram per square centimeter, which cannot account for the high weight-loss values associated with many of the alloys investigated.

Figure 5 shows photomicrographs of the metal-oxide interface, depletion zone, and unaffected matrix of several alloys after oxidation at 1900° F. The surface oxide is not evident because it was removed to obtain weight-loss measurements. Several interesting aspects pertaining to the oxidation process in these alloys may be observed. The interface between the unaffected matrix and the depletion zone is more clearly defined for vacuum-melted TAZ-8A than for the argon-melted material. This suggests that the oxidation process from which the depletion zone arises proceeds more uniformly in the vacuum-melted material. A marked difference exists between the microstructures of the vacuum and argon-melted TAZ-8A alloy. The aluminum-rich (white) gamma prime type particles, shown by arrows in figure 5, are more massive in the argon-melted material than in the vacuum-melted material. Electron-probe microanalyses indicated that these regions contained approximately 50 percent more aluminum than the nominal composition of 6 percent. Both the size and distribution of the aluminum rich white phases in the vacuum-melted alloy as compared with the argon-melted alloy suggest that aluminum would be made more readily and uniformly available to the surface in the vacuum-melted material. The vacuum-melted material, therefore, might be expected to have improved oxidation resistance, as observed in figure 3.

The photomicrographs of figure 5 also show that the depletion zone depth is approximately the same for all the alloys except René 41. The latter alloy, after exposure for 100 hours, had a substantially greater depletion zone than the other alloys after 310 hours. This indicates that René 41 may be more subject to a loss of strength because of the depletion of strengthening phases upon longtime exposure to elevated temperatures. Since this depletion is a surface associated phenomenon, it could become a severe problem in thin sections exposed to oxidizing environments.

In order to place the oxidation data in a more useful perspective, the total affected depths (external scale plus depletion zone) due to oxidation of TAZ-8A and René 41 are compared in table 3. Since the external scale was removed to obtain weight-loss data and since it is in any case extremely difficult to retain in position to make accurate measurements, a minimum scale thickness was calculated from weight-loss and density measurements. Typical depletion zone depths were measured from photomicrographs of oxidized samples. Both the external scale and the depletion zone are substantially smaller for TAZ-8A than for René 41. For example, the total affected depth for vacuum-melted TAZ-8A was approximately an order of magnitude less than that of René 41. These calculations are subject to a degree of error because of uncertainty regarding the exact amount of the external scale and possible dimensional variations in the test specimens. Nevertheless, they give a useful relative indication of the depth to which oxidation affects the microstructure of these alloys.

Also included in table 3 are data from reference 11 for Hastelloy X which indicate that it has a greater affected zone depth after 100 hours exposure at 1900° F than TAZ-8A after 300 hours. Of course, as noted previously, differences in investigative procedures can introduce uncertainties in such a comparison.

The results of an electron-probe microanalysis of an argon-melted TAZ-8A oxidation specimen along a line extending from the exposed surface, through the depletion zone, and into the matrix are shown in figure 6. The analysis was made on a sample that was exposed for 290 hours at 1900° F. The concentration of the major alloying elements is plotted against distance from the oxide-metal interface. The curve in the figure is stopped at a distance of 6 microns from the outer edge of the specimen because of edge effects. An abrupt change generally occurred in the concentration of the major alloying constituents at the matrix-depletion-zone interface. Unexpected discontinuities at this interface, such as those shown for columbium, tantalum, tungsten, and chromium, may be explained by the presence of an unidentified particle along the probe trace. A reduction in aluminum concentration was evident throughout the depletion zone. This observed depletion can reasonably be assumed to be the result of the formation of an aluminum-rich surface oxide.

Stress Rupture Properties

Stress rupture data for TAZ-8A are shown in figure 7. A least squares line has been drawn through the 15,000 pounds per square inch data. The TAZ-8 15,000 pounds per square inch isostress line (ref. 5) is also shown. At this stress the 500-, 100-, and 10-hour use temperatures for TAZ-8A are 1815°, 1895°, and 2010° F, respectively. TAZ-8A has lower stress-rupture life than TAZ-8 at temperatures up to 2050° F. The isostress lines for both alloys converge and cross at this temperature. The improved oxidation resistance of TAZ-8A may be reflected in this crossover of the isostress lines at high temperature. Limited data were obtained with TAZ-8A at a stress of 8000 pounds per square inch and these are also shown in the figure.

Figure 8 shows a bar-graph comparison of the 8000 pounds per square inch, 2125° F rupture life of TAZ-8A and four of the strongest known nickel- and cobalt-base alloys. TAZ-8A has a higher average rupture life (13 hours) at these conditions than do all of the other alloys. It is particularly interesting to note that its rupture life is greater than that of the cobalt-base alloys. Because of the higher melting point of cobalt and because these alloys do not depend for high temperature strengthening upon the gamma prime phase, which generally goes into solution below 2000° F, cobalt-base alloys might be expected to have higher use temperatures than nickel-base alloys. The good high-temperature performance (strength plus oxidation resistance) of TAZ-8A suggests that it may afford advantages for low-stress components of turbojet engines such as stator vanes in the range of temperatures from 2000° F to somewhat above 2100° F.

The tensile properties of TAZ-8A in cast and sheet form are shown in figure 9. Above 1400° F, the as-cast ultimate tensile strength decreased continually with increasing temperature, ranging from approximately 129,000 pounds per square inch at 1400° F to 6000 pounds per square inch at 2200° F. Between 1600° and 2000° F elongation remained reasonably constant at approximately 5 percent and then decreased to about 2 percent at 2100° F. Consideration of the sheet data indicates that a heat treatment has been achieved that maintained as-rolled strength at temperatures over 1400° F and substantially improved the ductility of the heat-treated sheet above 1800° F. Elongation of the as-rolled sheet ranged from approximately 3 percent at room temperature to 20 percent at 2200° F. Elongation of the heat-treated sheet began to exceed that of the as-rolled sheet above 1800° F and reached a maximum of 55 percent at 2200° F. The high elongations of the heat-treated sheet at 2100° and 2200° F suggest that it might be fabricable into complex shapes at these temperatures.

The ultimate tensile strengths of TAZ-8A in both cast and sheet form are compared in figure 10 at several temperatures with representative wrought and cast alloys. In sheet form TAZ-8A is approximately 50 percent stronger than René 41 sheet at 1600° and 1800° F. As-cast, TAZ-8A is comparable to the other cast nickel-base alloys at all three temperatures.

Workability

Workability potential of TAZ-8A was demonstrated by rolling argon-melted slabs, 0.11-inch thick, into sheet strips approximately 0.020-inch thick. Figure 11 shows an as-cast strip and an untrimmed as-rolled sheet strip. Some edge cracking of the sheet occurred during the 1900° F rolling operation. It should be emphasized that the process of making sheet by rolling a cast thin slab is a somewhat specialized one. The fine grain size that can be obtained in a thin slab contributes to rollability of the alloy in that impurities that normally congregate at grain boundaries are more widely distributed. Although the alloy was successfully rolled it has not been demonstrated to be a wrought alloy in the conventional sense of the word. Nevertheless, this work suggests that the alloy may be worked under closely controlled conditions and thereby fulfill requirements that cannot normally be met by other high-strength cast nickel-base alloys.

Impact Resistance

The average room-temperature Charpy impact resistance (unnotched) of TAZ-8A in the as-cast condition was 24 foot-pounds. This is somewhat lower than that of TAZ-8, which had an average impact resistance of 33 foot-pounds but considerably greater than that of another high-strength cast nickel-base alloy, Nicrotung, which had an average impact resistance of 9.7 foot-pounds (ref. 5). The Izod impact resistances of TAZ-8 and Nicrotung were both greater than 62.5 inch-pounds (ref. 5). It is interesting to note that other alloys with lower Izod impact resistance than this were successfully tested as turbojet engine buckets (ref. 12). Of course, as is the case for many nickel-base alloys, longtime exposure at elevated temperatures may result in the formation of embrittling phases which could reduce impact resistance. This aspect remains to be investigated.

Hardness

Rockwell A hardness readings for TAZ-8A ranged from 71.0 to 71.5 and averaged 71.2. If a standard conversion table for steel is used, the average Rockwell A hardness would be equivalent to Rockwell C hardnesses of 41 to 42, the same as the as-cast hardness of TAZ-8 (ref. 5).

Metallography

Photomicrographs of as-cast TAZ-8A obtained by argon and vacuum-melting are shown in figure 12. The microstructures of the argon- and vacuum-melted samples are generally similar, although some differences are discernible. The vacuum-melted material has smaller, more evenly distributed gamma-prime type particles. The massive carbides and/or carbonitrides that appear in the argon-melted material are absent in the vacuum-melted condition.

Photomicrographs of the as-rolled and heat-treated TAZ-8A 0.020-inch sheet are shown in figure 13. Sections were taken transverse to the rolling direction. The gamma-prime type phase has clearly been deformed by the rolling process. The carbides and/or carbonitrides remained unaffected by rolling although subsequent heat treatment greatly affected their appearance. The matrix precipitate has clearly been refined by rolling as compared with the as-cast material.

SUMMARY OF RESULTS

The following major results were obtained from this investigation to provide a nickel-base alloy with improved high temperature oxidation resistance and good elevated temperature strength for aerospace applications.

1. TAZ-8A, a high-strength nickel-base alloy with very good oxidation resistance was developed. Its nominal composition in weight percent is 2.5 col-

umbium, 8 tantalum, 6 chromium, 6 aluminum, 4 molybdenum, 4 tungsten, 1 zirconium, 0.125 carbon, 0.004 boron, and the balance nickel.

2. In oxidation tests, vacuum-melted TAZ-8A had a weight gain of 1.8 megawatt per square centimeters after 310 hours in air at 1900° F. An argon-melted 0.0215-inch rolled sheet specimen had a weight gain of 0.5 milligrams per square centimeter after 8 hours exposure at 1900° F. The alloy was substantially better in high temperature oxidation resistance than other representative nickel-base alloys when compared on the base of weight gain and weight loss.

3. The alloy has good as-cast stress-rupture properties. At a stress of 15,000 pounds per square inch, the 500-, 100-, and 10-hour use temperatures were 1815°, 1895°, and 2010° F, respectively. At 2125° F and a stress of 8000 pounds per square inch, the alloy had a rupture life of 13 hours and compared favorably with some of the strongest known nickel- and cobalt-base alloys.

4. Ultimate tensile strenghs of the as-cast alloy ranged from maximum values of 130,500 pounds per square inch at room temperature to 8000 pounds per square inch at 2200° F. These values compare with ultimate strengths of 240,000 pounds per square inch and 6500 pounds per square inch for the as-rolled material. By heat treating, the as-rolled strength was maintained at temperatures above 1400° F and substantially improved ductility was achieved above 1800° F.

5. The TAZ-8A alloy was hot-rolled from cast slabs 0.11-inch thick to a thickness of 0.020 inch on a conventional rolling mill. The reductions obtained indicate that the alloy has at least limited workability potential.

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TABLE I. - ALLOY COMPOSITIONS

(a) Nominal Compositions of Alloys Investigated

Alloys	Composition, weight percent									
	Ta	Cr	Al	Mo	W	Cb	Zr	C	B	Ni
1	8	6	6	4	4	0	1	0.125	0.004	Balance
2						0.5				
3						1.0				
[a]4						2.5				
5						3.5				
6						5.0				
7						7.5				
8						10.0				

[a]Alloy referred to as TAZ-8A.

(b) Composition of Random Heats of TAZ-8A

Condition	Composition, weight percent									
	Ta	Cr	Al	Mo	W	Cb	Zr	C	B	Ni
Vacuum melted	8.02	5.93	5.70	3.70	3.84	2.21	0.64	0.15	0.004	Balance
Argon melted	7.89	5.74	5.66	3.99	(a)	2.44	.94	.136	.004	
Argon melted	7.96	5.91	5.59	4.03	3.83	2.38	.85	.13	.006	
Argon melted	7.92	5.92	5.54	3.94	3.81	2.45	1.06	.14	.005	

[a]Tungsten analysis not definitive.

TABLE II. - PURITY OF

ALLOYING ELEMENTS

[The purities are those reported by the supplier.]

Element	Minimum purity, percent
Ni	99.9
Ta	99.7
W	99.9
Mo	99.5
Cr	99.8
Al	99.88
Cb	99.6
C	99.5
B	99.5

TABLE III. - COMPARISON OF AFFECTED ZONE DEPTHS

Alloy	Exposure condition		External scale thickness, mils	Depletion zone thickness, mils	Total affected depth, mils
	Time, hr	Temperature, °F			
René 41	100	1900	0.3	3.0	3.3
Argon-melted TAZ-8A	310	1900	.1	0.8	0.9
Vacuum-melted TAZ-8A	310	1900	.1	.3	.4
Haystelloy X[a]	100	1900	---	~2.0	>2.0

[a]Reference 11.

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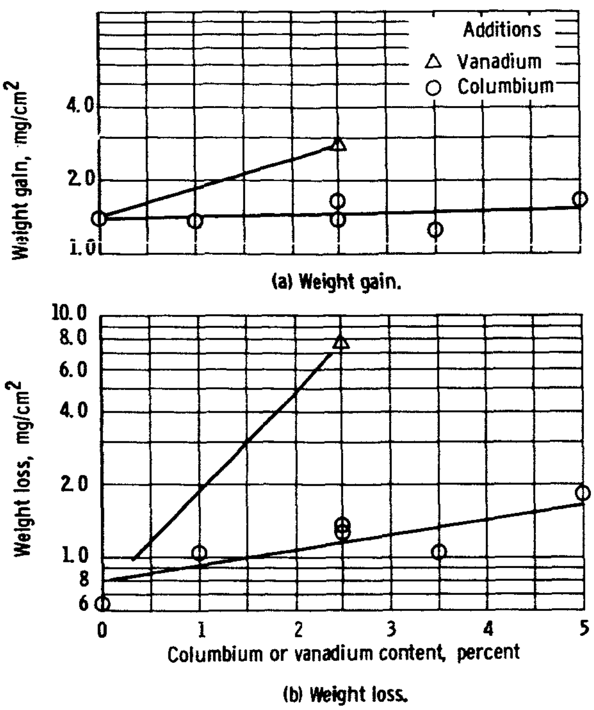


Figure 1. - Effect of columbium and vanadium additions on oxidation resistance of modified TAZ-8 alloy after 50 hours at 1900° F.

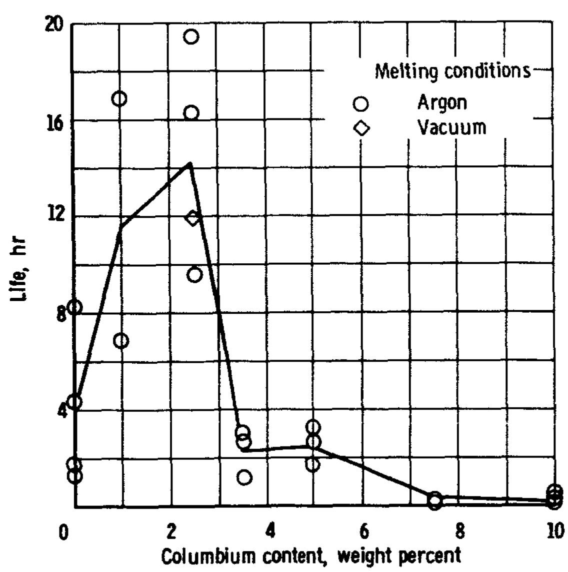
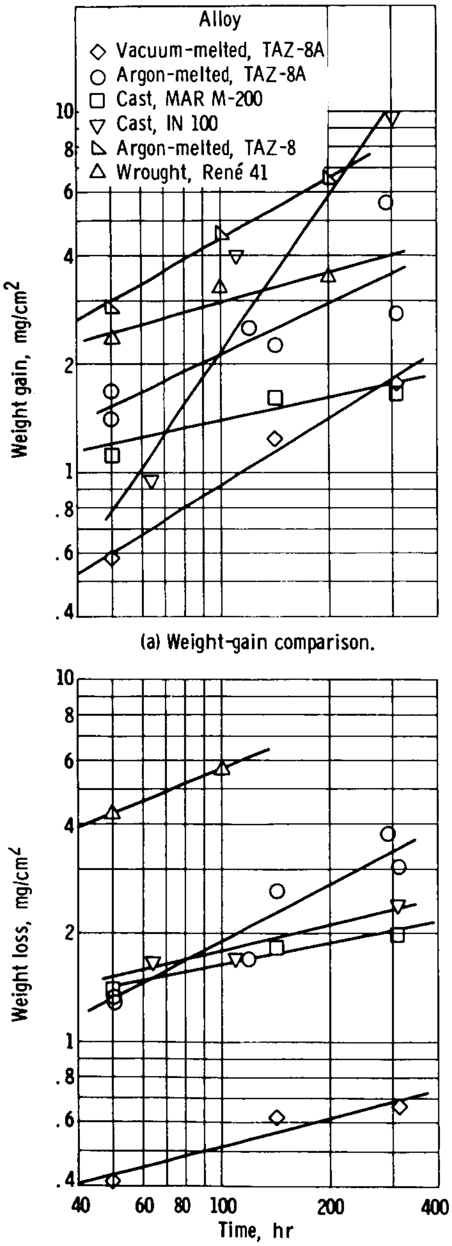
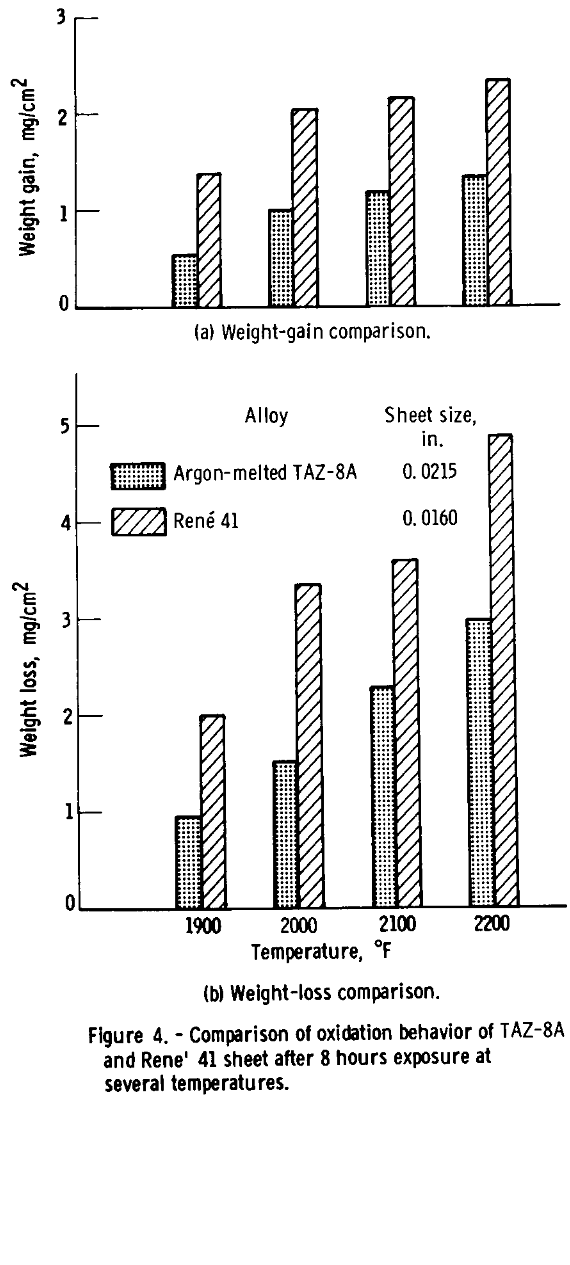


Figure 2. - Effect of columbium additions on stress-rupture life at 2000° F and 15 000 psi of modified TAZ-8 alloy.



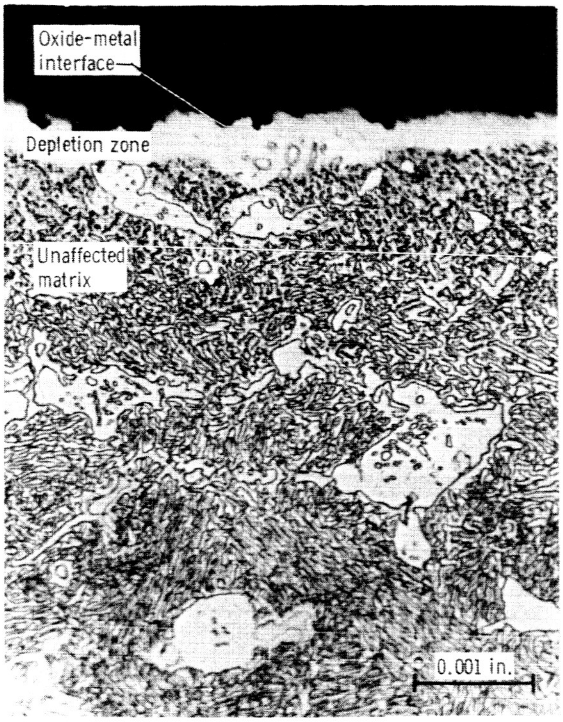
(b) Weight-loss comparison.

Figure 3. - Oxidation behavior of several nickel-base alloys at 1900° F.

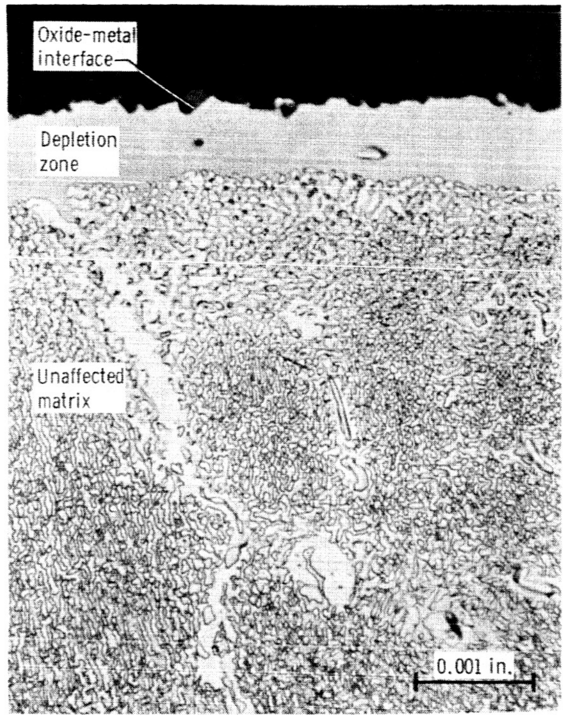


(b) Weight-loss comparison.

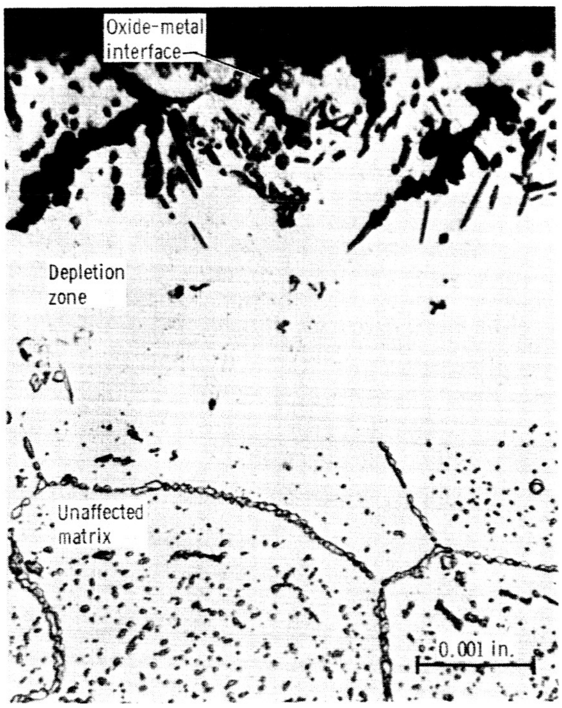
Figure 4. - Comparison of oxidation behavior of TAZ-8A and Rene' 41 sheet after 8 hours exposure at several temperatures.



(c) IN 100; exposure, 304 hours.



(d) MAR M-200; exposure, 310 hours.



(e) Rene' 41; exposure, 100 hours.

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Figure 5. - Concluded. Photomicrographs of oxidation specimens in vicinity of exposed surface after ozidation at 1900° F. X750.

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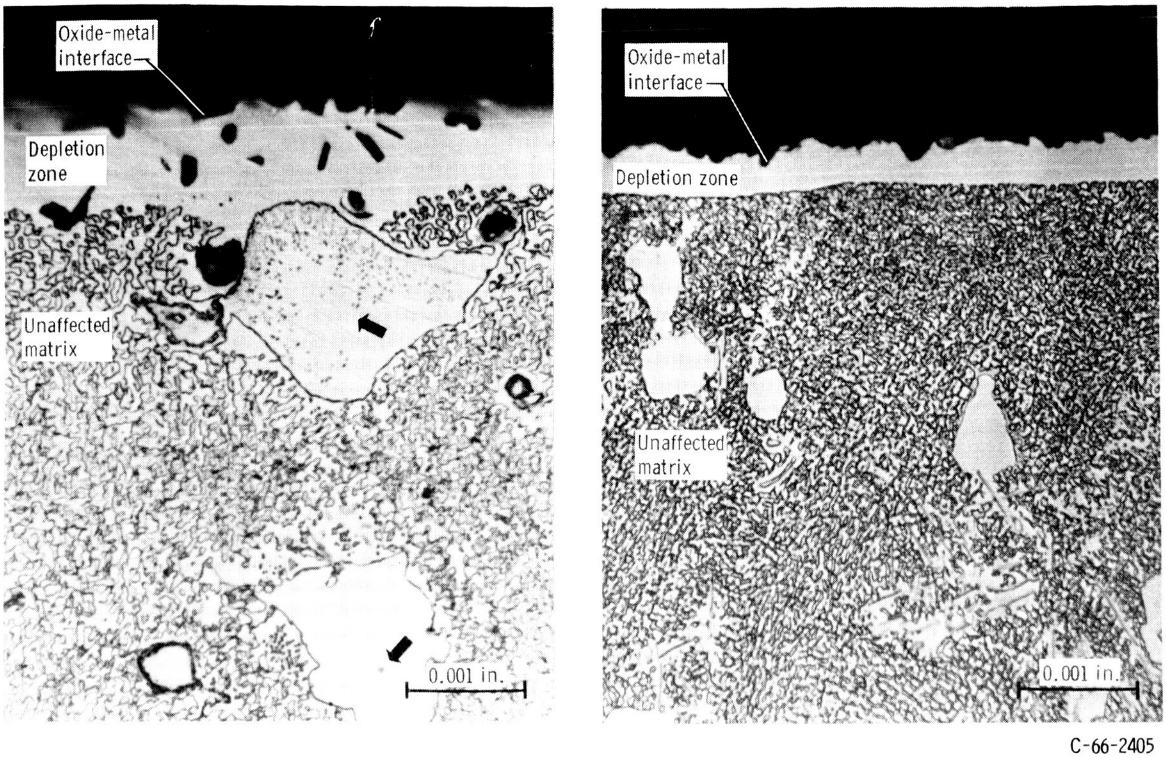

(a) Argon-cast TAZ-8A; exposure, 310 hours.

(b) Vacuum-cast TAZ-8A; exposure, 310 hours.

Figure 5. - Photomicrographs of oxidation specimens in vicinity of exposed surface after oxidation at 1900° F. X750.

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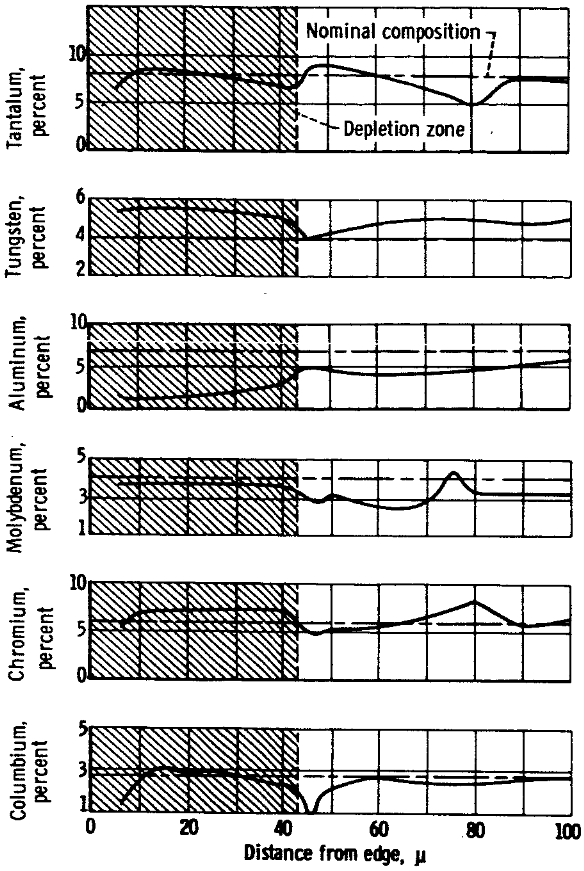

Figure 6. - Distribution of alloying elements near surface of argon-melted TAZ-8A; exposed 290 hours at 1900° F.

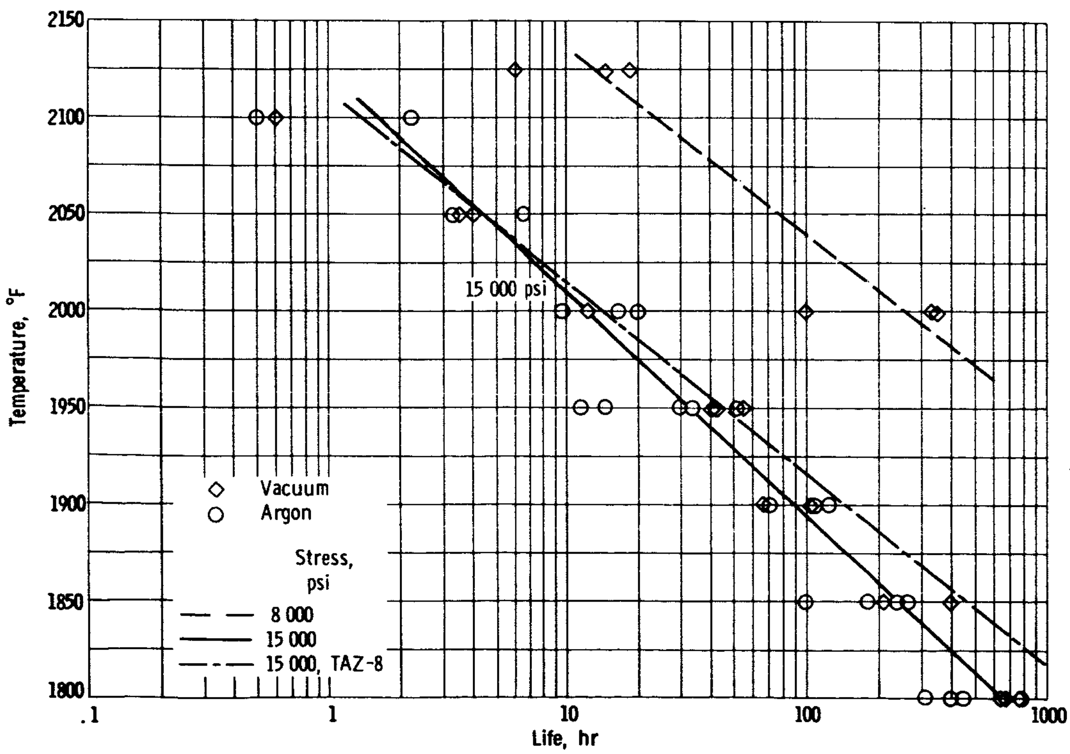

Figure 7. - As-cast stress rupture properties of TAZ-8A with 15 000 psi TAZ-8 isostress line superimposed.

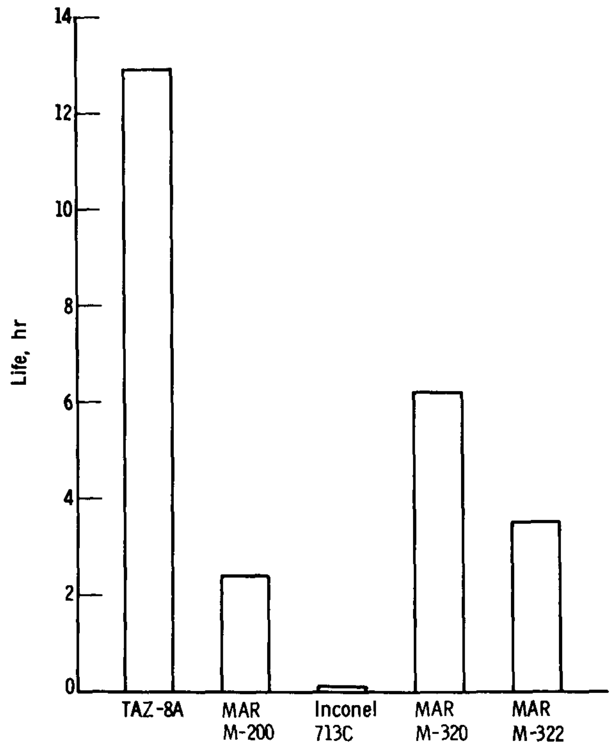

Figure 8. - Stress-rupture comparison of several nickel- and cobalt-base alloys at 8000 psi at 2125° F in air. (MAR M-320 and MAR M-322 data are from Thompson Ramo Wooldridge, Inc.)

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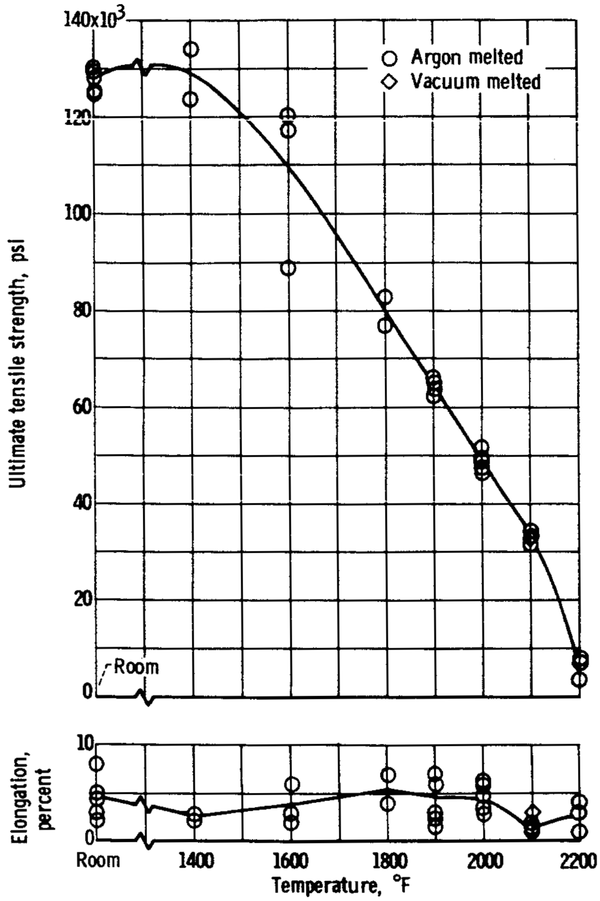
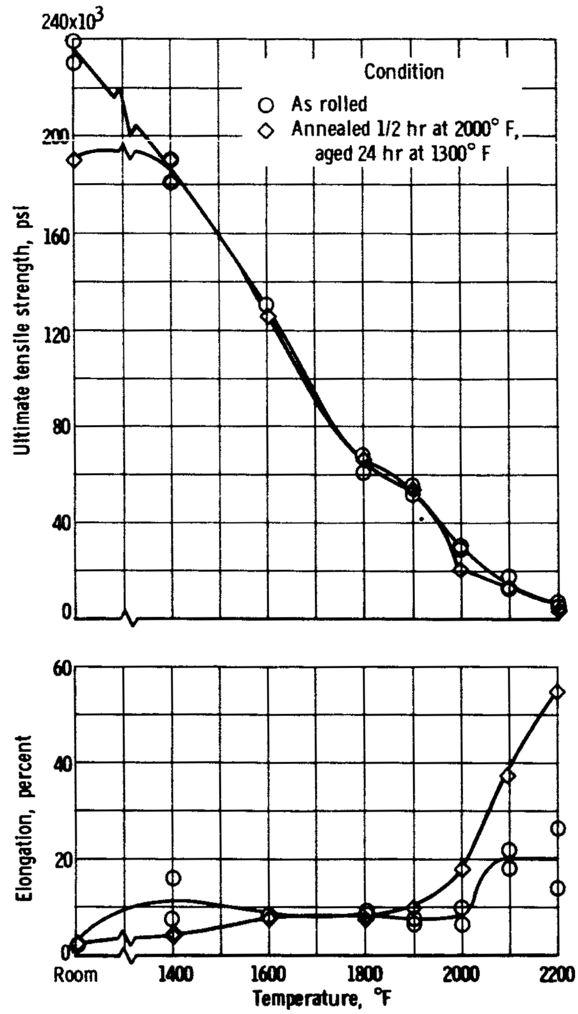


(a) As-cast.

Figure 9. - Tensile properties of TAZ-8A alloy.



(b) Sheet.

Figure 9. - Concluded. Tensile properties of TAZ-8A alloy.

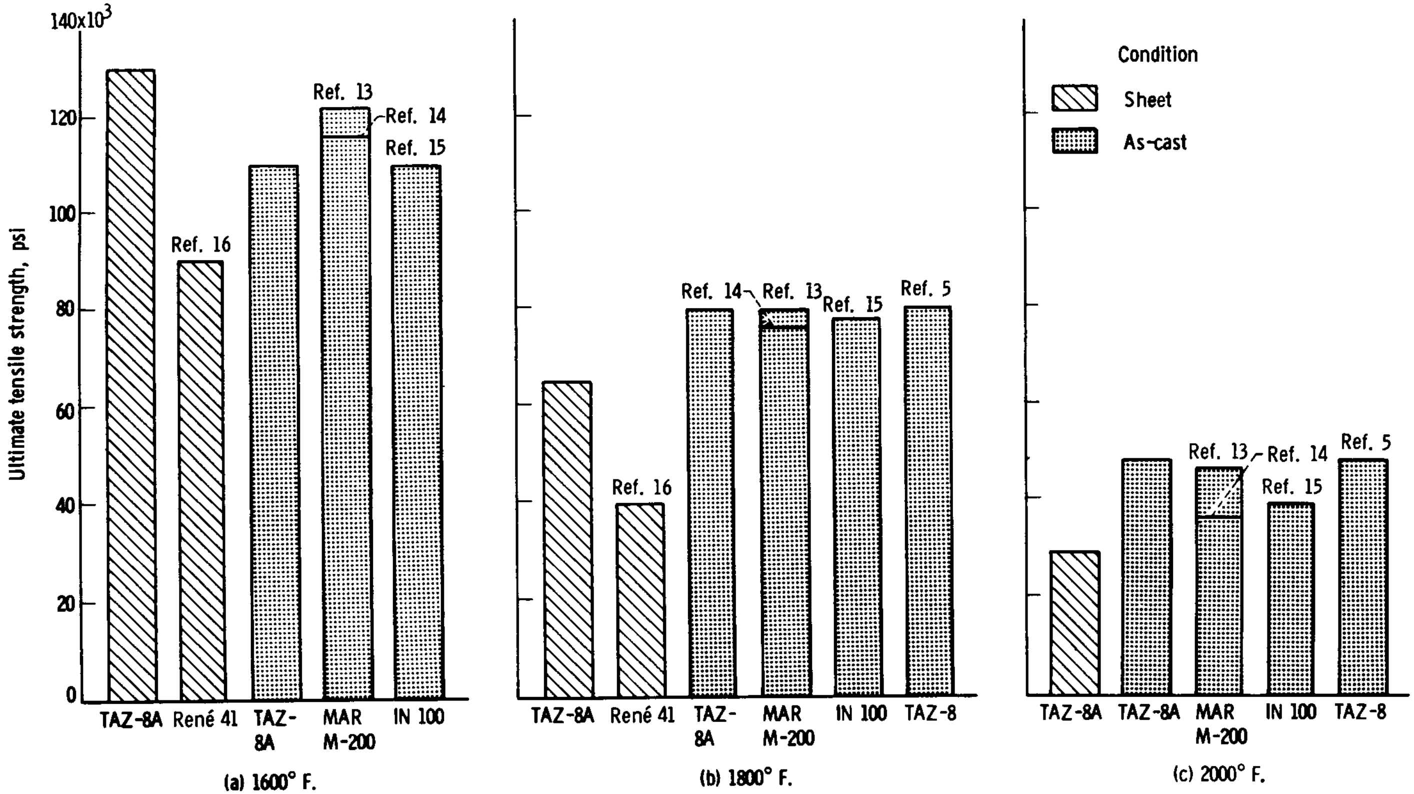


Figure 10. - Ultimate tensile strength of TAZ-8A and several nickel-base alloys in sheet and cast form at various temperatures.

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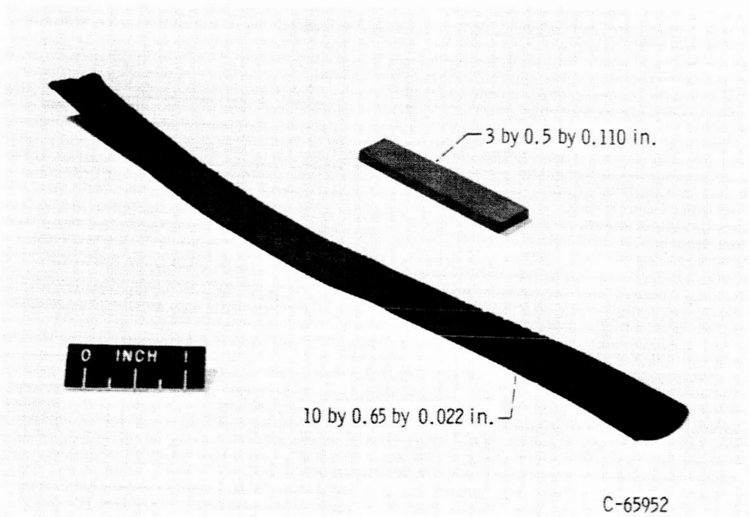
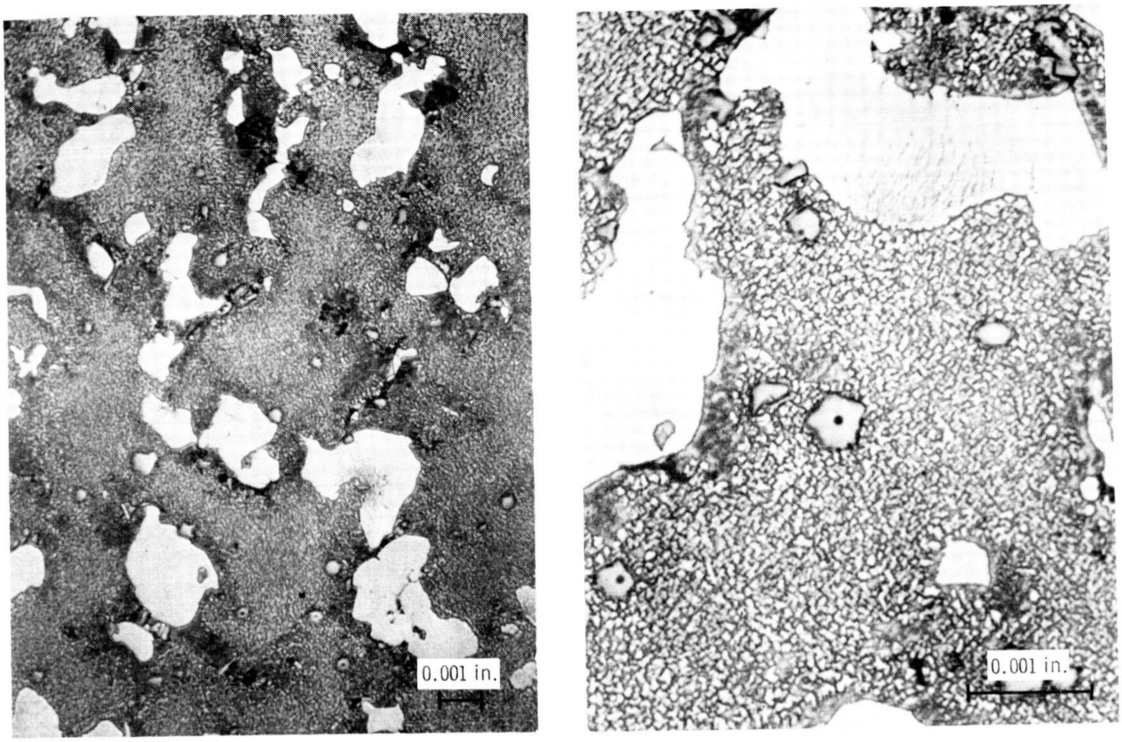
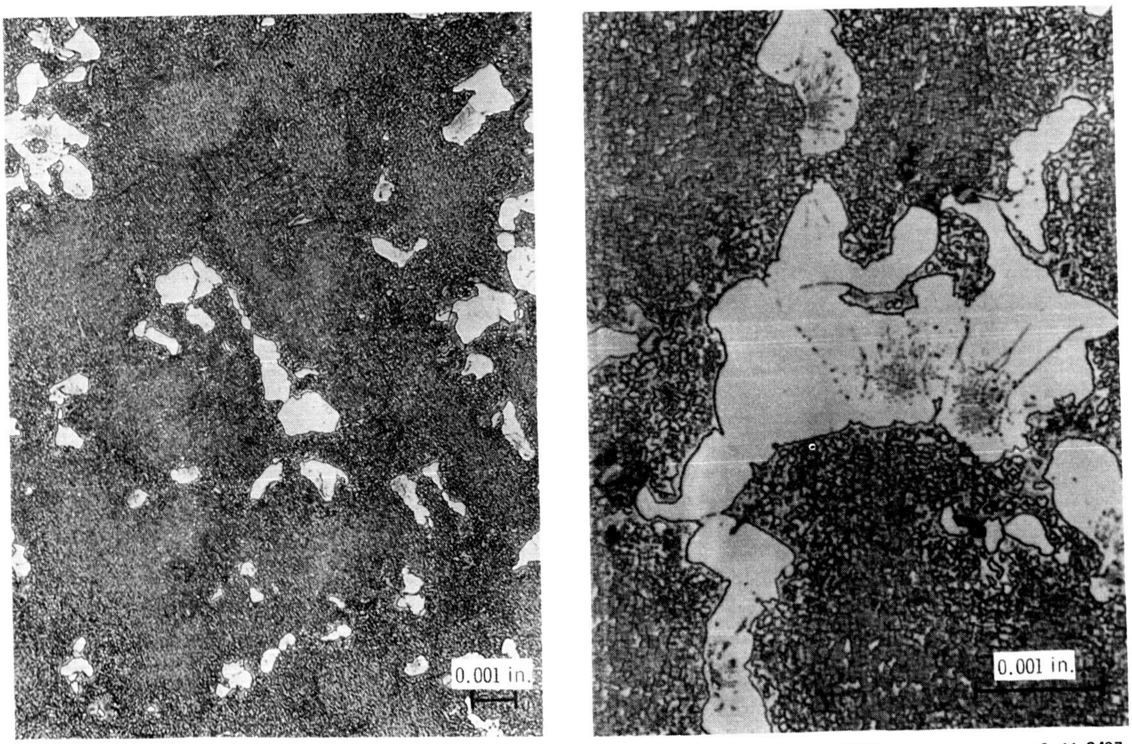


Figure 11. - TAZ-8A alloy before and after rolling at 1900° F.



X250. X750.

(a) Argon melted.



X250. X750. C-66-2407

(b) Vacuum melted.

Figure 12. - As-cast microstructure of TAZ-8A alloy.

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(a) As rolled.

(b) Heat treated 1/2 hour, 2000° F; 24 hours, 1300° F. C-66-2408

Figure 13. - Microstructure of 0.020-inch TAZ-8A alloy sheet. X750.