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HIGH-TEMPERATURE STRENGTH OF REFRACTORY-METAL WIRES AND CONSIDERATION FOR COMPOSITE APPLICATIONS

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16. Abstract

Tensile and stress-rupture tests were conducted on wires of W-Hf-C, W-Re-Hf-C, ASTAR 811C (a tantalum alloy), and B-88 (a columbium alloy) at room temperature, 1093° C (2000° F), and 1204° C (2200° F). Metallographic examinations were also made of the wire microstructure after testing. Ultimate tensile strength values up to 2170 meganewtons per square meter (314 000 psi) at 1093° C (2000° F) and 1940 meganewtons per square meter (281 000 psi) at 1204° C (2200° F) were obtained for W-Re-Hf-C wire. The best strength values obtained for a 100-hour rupture life were, 1410 meganewtons per square meter (205 000 psi) at 1093° C (2000° F) and 910 meganewtons per square meter (132 000 psi) at 1204° C (2200° F) for W-Re-Hf-C wire. The properties obtained suggested that the wires studied showed promise as potential fiber reinforcement in the 1093° to 1204° C (2000° to 2200° F) temperature range.

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HIGH-TEMPERATURE STRENGTH OF REFRACTORY-METAL WIRES AND CONSIDERATION FOR COMPOSITE APPLICATIONS

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SUMMARY

Tensile and stress-rupture tests were conducted on refractory-metal alloy wires at room temperature, 1093° C (2000° F), and 1204° C (2200° F). Wires of W-Hf-C, W-Re-Hf-C, ASTAR 811C (a tantalum-base alloy), and B-88 (a columbium-base alloy) were tested in the 0.038- to 0.051-centimeter- (0.015- to 0.020-in.-) diameter range. The wires were tested in a vacuum of 1×10^{-6} to 5×10^{-5} torr in tension and for rupture. The wire specimens were examined after fracture, and reduction-in-area measurements were made. Metallographic examinations were also made of the wire microstructure after testing.

The highest ultimate tensile strength values obtained were 2170 meganewtons per square meter (314 000 psi) at 1093° C (2000° F) and 1940 meganewtons per square meter (281 000 psi) at 1204° C (2200° F) for W-Re-Hf-C wire. The ultimate tensile strength/density value obtained for the W-Re-Hf-C wire was 11.4×10^{3} meters (450×10^{3} in.) at 1093° C (2000° F), and 10.2×10^{3} meters (400×10^{3} in.) at 1204° C (2200° F). The best strength values obtained for a 100-hour rupture life were 1410 meganewtons per square meter (205 000 psi) at 1093° C (2000° F) and 910 meganewtons per square meter (132 000 psi) at 1204° C (2200° F) for W-Re-Hf-C wire.

The tensile and stress-rupture strengths of the wires investigated were superior to those reported for rod, bar, or sheet forms of refractory metals with the exception of B-88. The superior strengths obtained suggested that the wires studied showed promise as potential fiber reinforcement in the 1093° to 1204° C (2000° to 2200° F) temperature range. These results also suggest that it may be possible to produce W-Re-Hf-C fiber reinforced nickel or cobalt superalloys with over four times the tensile strength and up to ten times the 100-hour rupture strength at 1093° C (2000° F) of the strongest superalloys. Further, it may be possible to produce B-88 columbium-alloy-fiber - superalloy composites with a specific 100-hour rupture strength adequate for turbine blade service at 1093° C (2000° F). A solid turbine blade of B-88 wire-superalloy composite would be 10 to 18 percent heavier than a conventional superalloy blade but may permit a 111° C (200° F) increase in operating temperature.

INTRODUCTION

The attractive high-strength potential of fiber composites is largely based on the properties of the fibers. As such, there is a need for fibers with improved properties and for fiber mechanical property data to aid in the selection and design of fiber-reinforced composite materials.

Refractory-metal alloy wires are of interest for fiber reinforcement of superalloy type matrix materials for use between 1093° C (2000° F) and 1204° C (2200° F) because of their high strength at these temperatures. In previous work (refs. 1 and 2) at the Lewis Research Center, composites of refractory-metal-fiber-reinforced, nickel-base alloys were produced that had stress-rupture strengths superior to conventional superalloys at use temperatures of 1093° C (2000° F) and 1204° C (2200° F). Strength for 1000-hour rupture life as great as six times that for the strongest conventional superalloys was obtained at 1093° C (2000° F). Even stronger composites would have been possible if higher strength fibers had been available. Research has been sponsored by the Lewis Research Center to fabricate stronger alloys into wire form. Alloys of tungsten, tantalum, and columbium having high creep resistance at temperatures of 1093° C (2000° F) and above were selected. The specific alloys were W-Hf-C, W-Re-Hf-C, ASTAR 811C (a tantalum alloy), and B-88 (a columbium alloy). These alloys were drawn into 0.051- and 0.038-centimeter- (0.020- and 0.015-in.-) diameter wire.

This investigation was conducted to determine the tensile and stress rupture properties of the materials cited above and to assess whether these materials could be considered for applications to metallic composite turbine blades of jet engines. Room-temperature tensile tests and elevated-temperature tensile and stress-rupture tests were conducted at 1093° and 1204° C (2000° and 2200° F). The wires were tested in a vacuum of 1×10^{-6} to 5×10^{-5} torr in tension and for rupture times up to 500 hours. The wire specimens were examined after fracture, and reduction-in-area measurements were made. Metallographic examinations were also made of the wire microstructure after testing to relate the observed structures to measured properties.

MATERIALS, APPARATUS AND PROCEDURE

Wire Material

Alloys of tungsten, tantalum, and columbium having high creep resistance at temperatures of 1093° C (2000° F) and above were selected to be drawn into wire form. The specific alloys selected were W-Re-Hf-C, W-Hf-C, ASTAR 811C (a tantalum alloy), and B-88 (a columbium alloy). These alloys were drawn into fine-diameter wires.

This work was done by two contractors. The fabrication procedure used by the contractors was not optimized to obtain the highest possible wire strength but, rather, was selected to successfully obtain the alloys in wire form.

A chemical analysis of the composition of each alloy is listed in table I. The W-Hf-C and W-Re-Hf-C alloys were drawn into wire in the fully hardened condition (no in-process anneals during working) by one contractor. Alloys ASTAR 811C, B-88, and an additional different lot of W-Hf-C were drawn by a different contractor using annealing treatments during the working process. The wire diameter tested for the W-Hf-C and W-Re-Hf-C alloys was 0.038 centimeter (0.015 in.), while that for B-88 and ASTAR 811C was 0.051 and 0.038 centimeter (0.020 and 0.015 in.). All wire was tested in the as-drawn, cleaned, and straightened condition.

Tensile Tests

The wire was tested in tension in a vacuum chamber at a vacuum of 1×10^{-6} to 5×10^{-5} torr with a constant-strain, screw-driven tensile machine. The strain rate used for all tests was 0.25 centimeter (0.1 in.) per minute. Tensile tests were conducted at room temperature, 1093° C (2000° F), and 1204° C (2200° F).

Stress-Rupture Tests

The equipment used to conduct constant-load, stress-rupture tests is shown in figure 1 and described in detail in reference 3. Wire specimens were cut to 38-centimeter (15-in.) lengths. Each specimen was clamped to a fixed mount, strung through a tantalum-wound resistance furnace, passed over a pulley, and attached to a weight which applied the required load. The weights were supported by retractable supports, while the furnaces and wire test specimens were heated to the test temperature and were stabilized. Microswitches were actuated by fallen weights as each specimen broke, thereby disconnecting power to the furnace and recording the time to fracture. The entire assembly was covered by a cooled metal bell jar. Testing was conducted in a vacuum of 1×10^{-6} to 5×10^{-5} torr. The test temperature was monitored with platinum - platinum-13-percent-rhodium thermocouples. The test temperature did not vary more than ±3° C (±5° F) during the course of the tests.

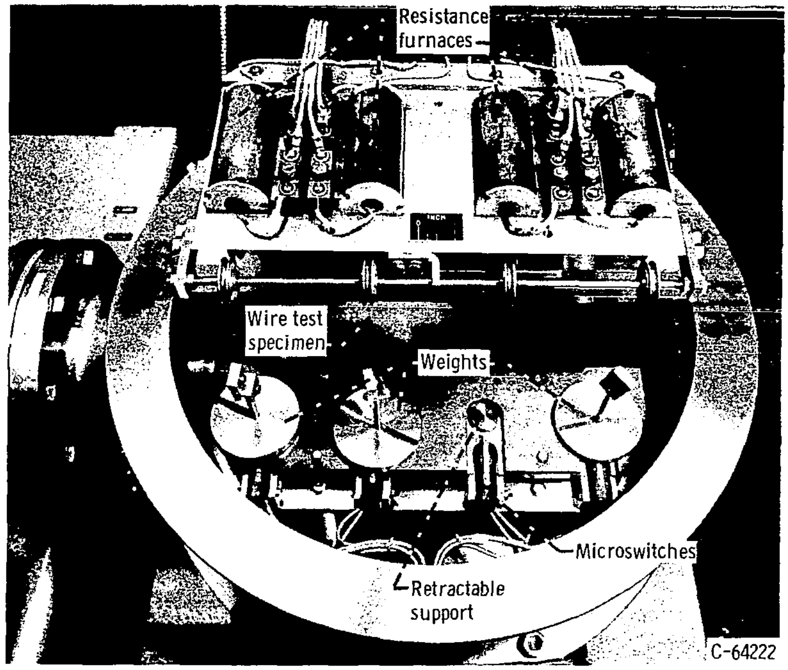


Figure 1. - Fiber stress-rupture testing apparatus.

Reduction-in-Area Measurements

After testing, the fracture area of each tensile and stress-rupture specimen was examined with a microscope at a magnification of 100. Reduction-in-area calculations were based on the difference between the known original wire area and the final area calculated from the average of two diametral measurements taken after testing at a magnification of 100.

Metallographic Analysis

After testing, a longitudinal section of the fracture edges of wire specimens were mounted in epoxy resin and metallographically polished with successively finer grit abrasive papers (to 600 grit size). The specimens were next polished successively with 3- and 0.5-micrometer diamonds, and a slurry of 0.3-micrometer alumina powder and water on a silk cloth.

The specimens were then etched with the solutions listed in the following table:

Wire material	Etch	Method of applying etch
W-Hf-C W-Re-Hf-C	30 cm^3 Lactic 10 cm^3 HF 10 cm^3 HNO_3	Swabbing
ASTAR 811C	60 cm^3 Lactic 40 cm^3 HNO_3 20 cm^3 HF	Immersion
B-88	90 cm^3 Lactic 30 cm^3 HNO_3 15 cm^3 HF 25 g NH_4F	Immersion

After etching, the samples were cleaned for several minutes in an ultrasonic bath of water and were given a final cleaning for 1 minute in an ultrasonic bath of ethyl alcohol. The specimens were then dried in a warm air blast, and the sample surfaces were further cleaned by dry-stripping with a replicating medium.

A two-step technique was used to replicate the wires. The samples were first replicated with 0.025 percent Mowital dissolved in chloroform and, after drying, they were reinforced with 1.5 percent Parlodion in amyl acetate. The two plastic layers were then dry-stripped with pressure-sensitive cellulose tape, shadowed with platinum carbon, and reinforced with a 0.01 micrometer layer of carbon. The replica was cut into grid-size squares and placed into an amyl acetate solution to remove the pressure-sensitive cellulose tape and to dissolve the Parlodion. The Mowital-carbon replica was then viewed in an electron microscope at magnifications of 9000 to 58 000, and photographs were taken at magnifications of 9000 to 12 000.

MECHANICAL PROPERTY DATA

Tensile Properties

The room-temperature, 1093° C (2000° F), and 1204° C (2200° F) tensile properties of the wire materials investigated are listed in table II. The tensile strength of tungsten wire containing 2 percent thoria was previously determined (ref. 4) and is included in the table for comparison.

Room temperature. - The tungsten-alloy wires were superior in tension at room temperature to the tantalum- and columbium-base alloys investigated. The hard-drawn W-Re-Hf-C wire material was the strongest wire material investigated, having a room-temperature tensile strength of 3160 meganewtons per square meter (458 000 psi). It is also interesting to note that the hard-drawn W-Re-Hf-C alloy wire is much more ductile at room temperature than the hard-drawn W-Hf-C alloy wire, having a reduction in area of 27.5 percent as compared with 1.9 percent for the hard-drawn W-Hf-C alloy wire. The tantalum-base alloy (ASTAR 811C) wire was weaker than the tungsten-alloy wires but slightly stronger than the columbium-base alloy (B-88) wire. The room-temperature tensile strength of the tungsten - 2-percent-thoria wire was slightly lower than that of the hard-drawn W-Re-Hf-C wire and the in-process-annealed W-Hf-C wire, and it was higher than that of the other wires investigated.

Elevated temperature. - The tungsten-base alloy wires were much stronger at 1093° and 1204° C (2000° and 2200° F) than either the tantalum- or columbium-base alloy wires studied. The tensile strength of the tantalum-base alloy (ASTAR 811C) wire also compares favorably with the tensile strength obtained for conventional tungsten lamp filament wire in the work of reference 4 (869 MN/m^2 (126 000 psi) at 1093° C (2000° F)). The W-Re-Hf-C wire had the highest tensile strengths of all the wires tested at 1093° and 1204° C (2000° and 2200° F), with 2170 and 1940 meganewtons per square meter (314 000 and 281 000 psi), respectively.

Figure 2 shows the percentage of the room-temperature tensile-strength retention of the various wire materials. The percentage of strength retention was calculated for two test temperatures, 1093° C (2000° F) and 1204° C (2200° F). The tungsten-alloy wires showed the best strength retention, while the columbium-alloy wires showed the poorest strength retention. The strength retention of the ASTAR 811C alloy wire appears good up to 1093° C (2000° F) and compares favorably with some of the tungsten-alloy wires. At 1204° C (2200° F), however, the strength retention of the tantalum-alloy wire was much lower than that of any of the tungsten-alloy wires. The columbium-alloy (B-88) strength retention was the least of the materials tested.

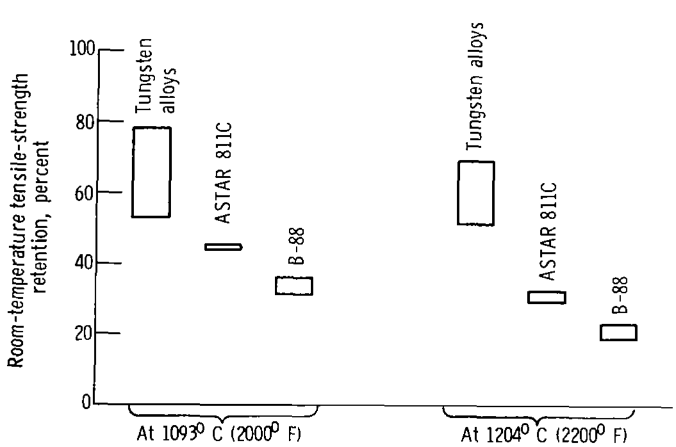


Figure 2. - Percentage of room-temperature tensile-strength retention for wires at two test temperatures.

Stress-Rupture Properties

Stress-rupture strength. - Results of stress-rupture tests on the wire materials studied are presented in table III and plotted as stress to cause rupture against rupture life in figures 3 to 6. Figure 3 is a plot of stress to cause rupture against rupture life for hard-drawn and in-process annealed W-Hf-C wire tested at 1093° and 1204° C (2000° and 2200° F). The rupture strength of the hard-drawn wire is greater than that of the in-process annealed wire at both temperatures. At 1204° C (2200° F), however, there is little superiority in rupture strength. The strongest fiber of all those tested in stress rupture was the hard-drawn W-Re-Hf-C wire. Figure 4 is a plot of the stress to cause rupture against rupture life for the W-Re-Hf-C wire tested at 1093° and 1204° C (2000° and 2200° F). The ASTAR 811C wire had lower stress-rupture strength values than the tungsten wires at both temperatures. Figure 5 is a plot of the stress to cause rupture

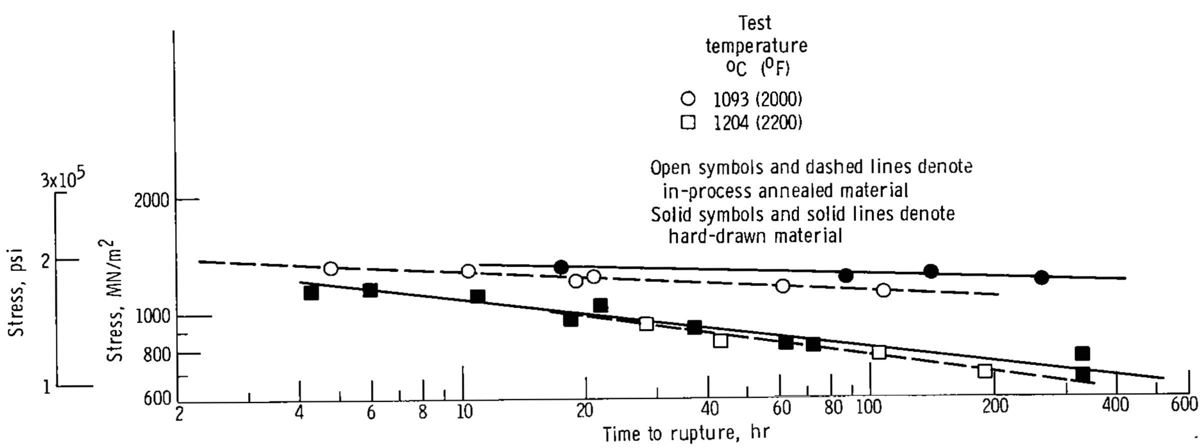


Figure 3. - Time to rupture as function of stress for W-Hf-C wire.

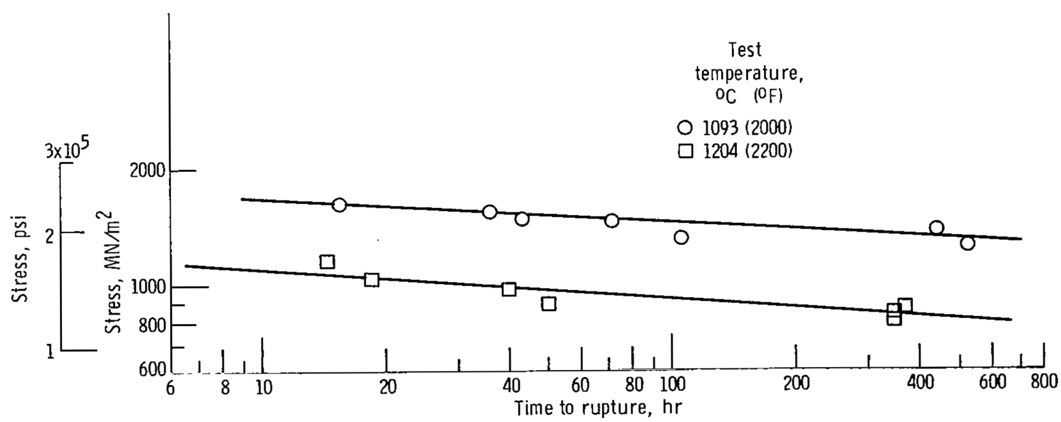


Figure 4. - Time to rupture as function of stress for W-Re-Hf-C wire.

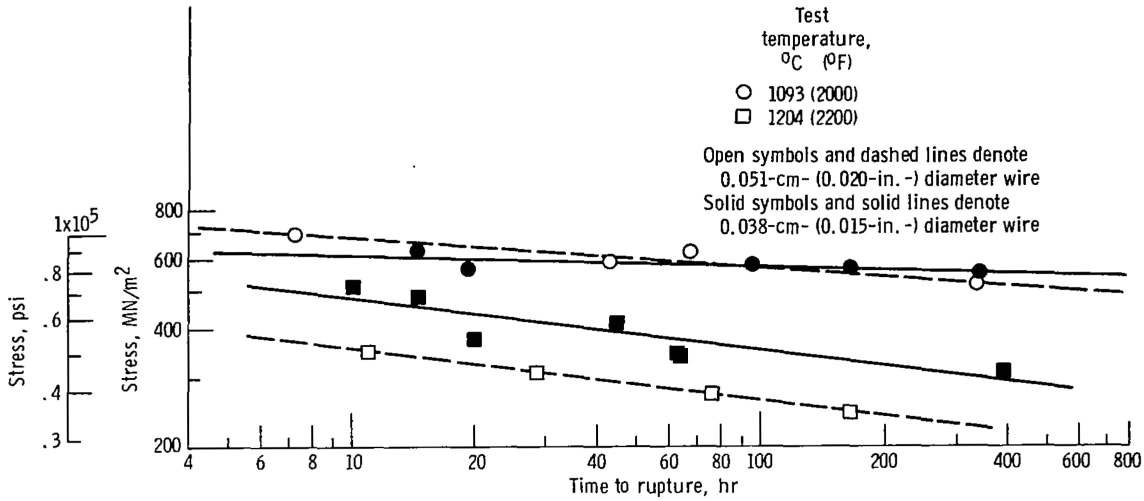


Figure 5. - Time to rupture as function of stress for ASTAR 811C wire.

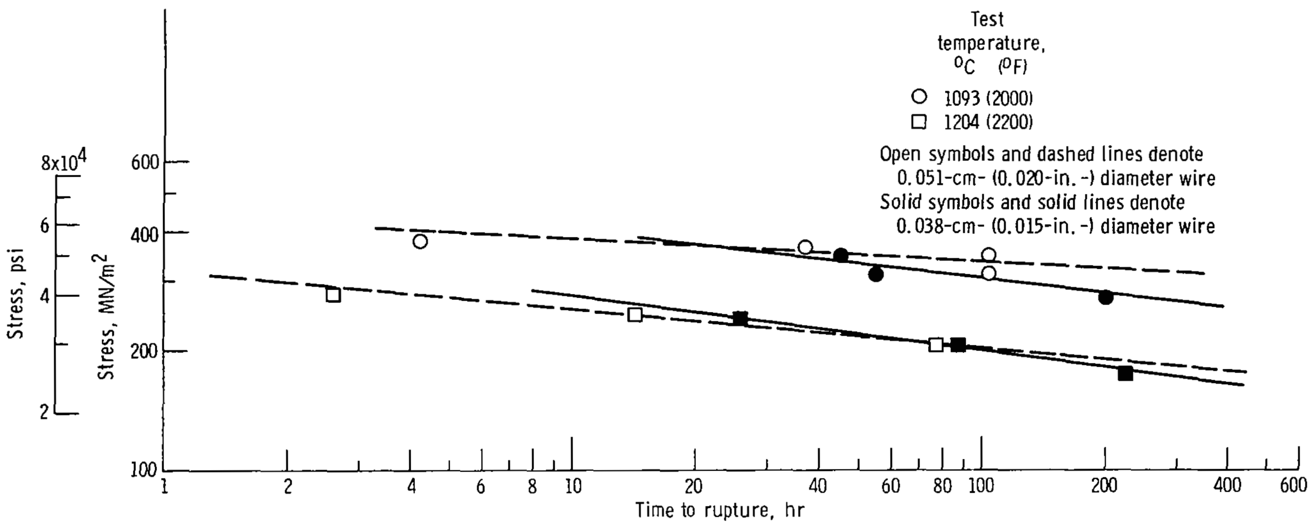


Figure 6. - Time to rupture as function of stress for B-88 wire.

against rupture life for both the 0.51- and 0.038-centimeter- (0.020- and 0.015-in.-) diameter ASTAR 811C wire tested at 1093° and 1204° C (2000° and 2200° F). At 1093° C (2000° F), the stress-rupture strength was nearly equivalent for both wire diameters. At 1204° C (2200° F), the 0.038-centimeter- (0.015-in.-) diameter wire was stronger in stress-rupture than the 0.051-centimeter- (0.020-in.-) diameter wire. A plot of stress to cause rupture against rupture life for 0.051- and 0.038-centimeter- (0.020- and 0.015-in.-) diameter B-88 wire is shown in figure 6. The B-88 wire was the weakest in stress-rupture of all the alloys studied. The 0.051- and 0.038-centimeter- (0.020- and 0.015-in.-) diameter wires had nearly equivalent strength in rupture at both temperatures.

In figure 7, the stress to cause rupture is plotted as a function of rupture life for the wires of all alloys tested at 1093° C (2000° F) so that their relative strengths and the slopes of the curves can be compared. With the exception of the 0.051-centimeter- (0.020-in.-) diameter ASTAR 811C wire and the 0.038-centimeter- (0.015-in.-) diameter B-88 wire, the alloy wire materials appear to have equivalent slopes for the stress - rupture-time curves at 1093° C (2000° F). The same type of plot for the 1204° C (2200° F) stress-rupture tests is shown in figure 8. The W-Re-Hf-C alloy and the 0.51-centimeter- (0.020-in.-) diameter B-88 wire stress-rupture against time curves have the lowest slopes at this temperature.

Stress-rupture ductility. - The elevated-temperature ductility of the wire specimens tested in this investigation was determined by reduction-in-area measurements (table III). Although considerable decrease in stress rupture ductility was obtained for some tungsten alloy specimens, there was no consistent trend. However, a fairly consistent decrease in ductility with time was observed for both the tantalum- and columbium-base alloys.

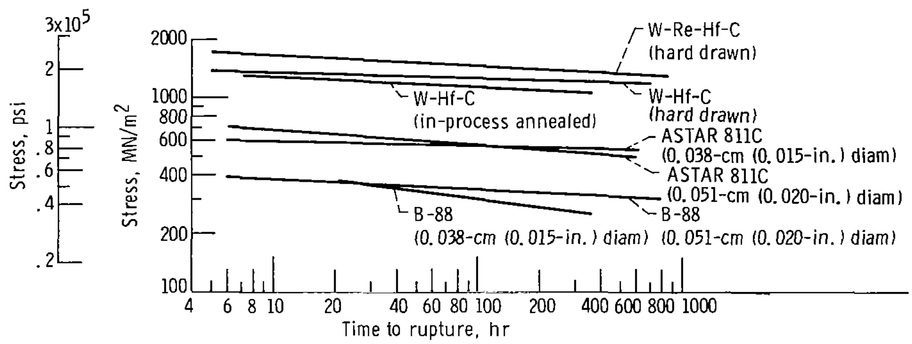


Figure 7. - Comparison of time to rupture as function of stress for wires tested at 1093° C (2000° F).

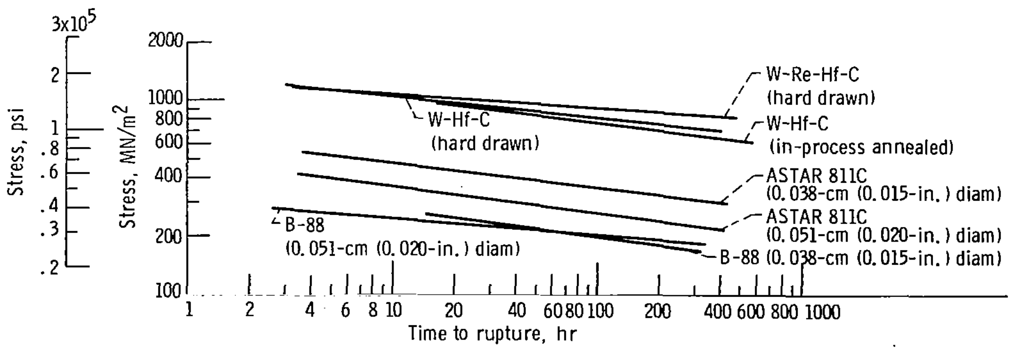


Figure 8. - Comparison of time to rupture as function of stress for wires tested at 1204° C (2200° F).

MICROSTRUCTURAL STUDY

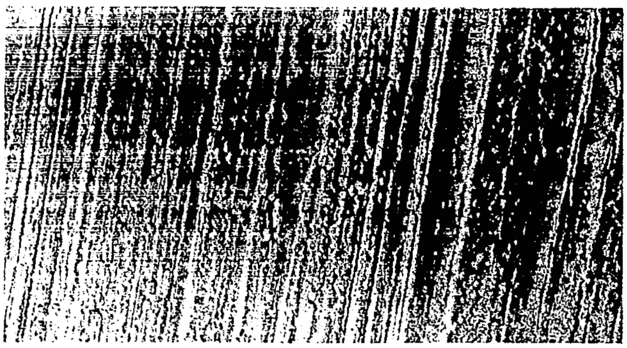
Tungsten-Base Alloys

Table IV provides a summary of the wire microstructure data as a function of exposure time and temperature.

Hard-drawn W-Hf-C. - Figure 9(a) is an electron photomicrograph of a hard-drawn W-Hf-C wire in the as-drawn condition. Heavily worked elongated grains are visible. Occasional large particles were observed. The largest particle observed was 0.05 micrometer. Small particles were evenly distributed throughout the wire and were approximately 0.015 to 0.040 micrometer in size and occupied approximately 1 percent of the area of the wire. The small particles are believed to be precipitates of HfC. The grains increased slightly in width, and a small degree of subgrain formation occurred for the specimen which failed after a long-time exposure at 1093° C (2000° F), as shown in figure 9(b). The small particles observed in this specimen were between 0.020 and 0.060 micrometer in size. Large particles were also observed in this specimen. The largest particle observed was 0.20 micrometer. Grain broadening was also observed for specimens exposed at 1204° C (2200° F), as shown in figures 9(c) and (d). The grains also were not as distinct as those of the specimens in the as-drawn condition and those exposed at 1093° C (2000° F).

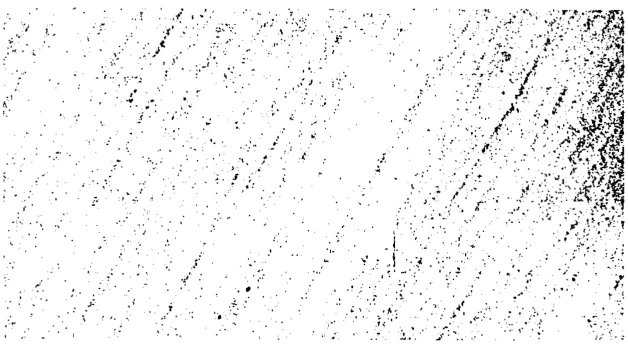
In-process annealed W-Hf-C. - Figure 10(a) is an electron photomicrograph of an in-process annealed W-Hf-C wire in the as-drawn condition. Heavily worked elongated grains are visible. Small particles were very sparsely distributed throughout the wire. The particle size ranged from 0.030 to 0.100 micrometer. The particles are believed to be HfC. Increased temperature and time of exposure resulted in grain broadening and a small degree of subgrain formation, as shown in figures 10(b) to (e).

Hard-drawn W-Re-Hf-C. - The microstructure of a hard-drawn W-Re-Hf-C wire in the as-drawn condition is shown in figure 11(a). Small particles were evenly distributed throughout the wire and ranged in size from 0.010 to 0.120 micrometer. Heavily worked elongated grains are visible. Figure 11(b) shows the microstructure of a specimen exposed at 1093° C (2000° F) for approximately 15 hours. The microstructure is similar to the microstructure of the as-drawn specimen. The microstructure of a specimen exposed at 1093° C (2000° F) for approximately 442 hours is shown in figure 11(c). Grain broadening, as well as some subgrain formation, has occurred. The small particles have not increased in size and range between 0.010 to 0.120 micrometer. Figures 11(d) and (e) show the microstructure of specimens exposed at 1204° C (2200° F). Grain broadening and partial recrystallization have occurred.

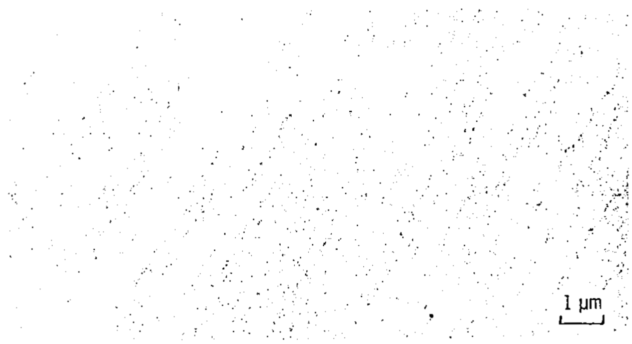


(a) As drawn.

(b) After 327.4 hours at 1093° C (2000° F).



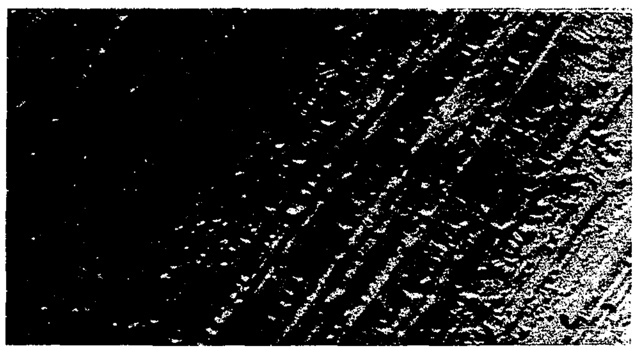
(c) After 11.1 hours at 1204° C (2200° F).



(d) After 334.1 hours at 1204° C (2200° F).

Figure 9. - Replica electron micrographs of hard-drawn W-Hf-C wire tested at various temperatures. X11 000. (Reduced 50 percent in printing.)

(a) As drawn.



(b) After 4.4 hours at 1093° C (2000° F).

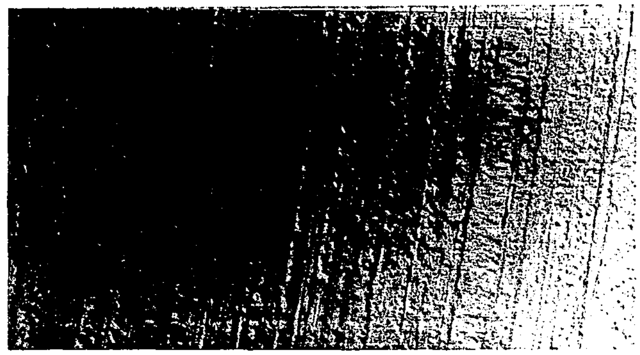
(c) After 108.3 hours at 1093° C (2000° F).

Figure 10. - Replica electron micrographs of in-process annealed W-Hf-C wire tested at various temperatures. X12 000. (Reduced 50 percent in printing.)

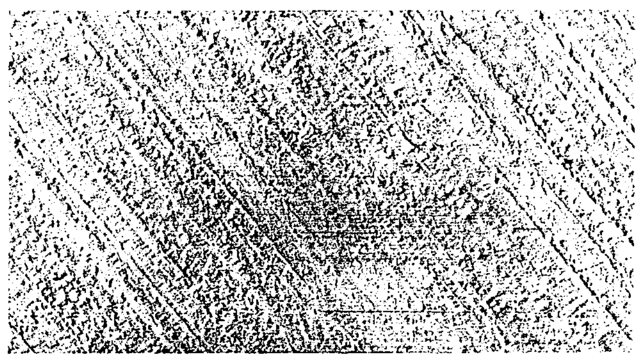
(d) After 28.3 hours at 1204° C (2200° F).

(e) After 188.4 hours at 1204° C (2200° F).

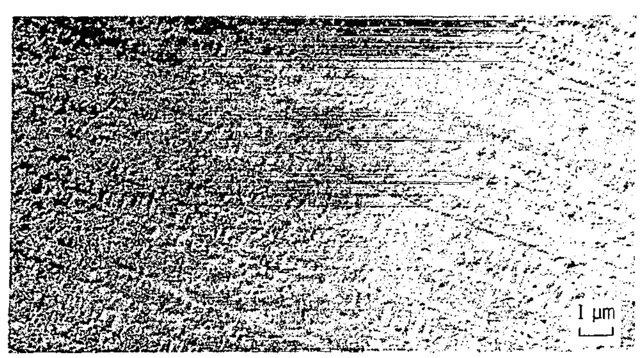
Figure 10. - Concluded.



(a) As drawn.

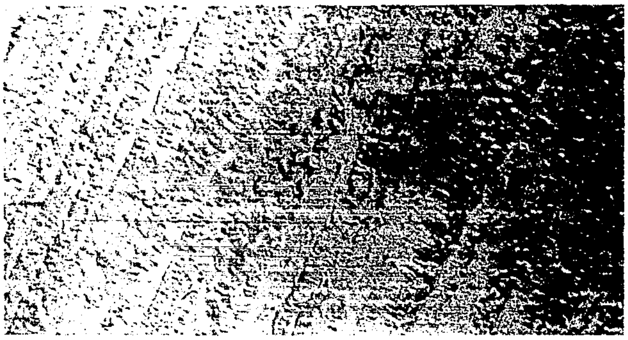


(b) After 15.6 hours at 1093° C (2000° F).

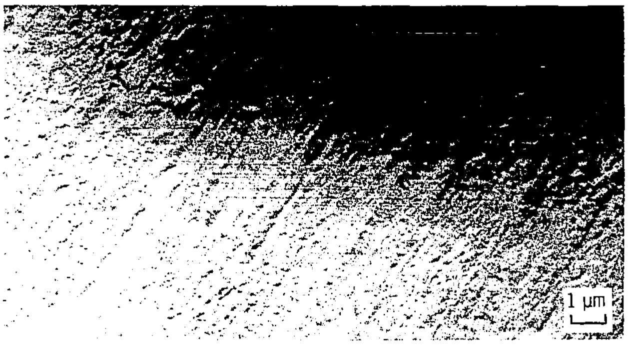


(c) After 442.6 hours at 1093° C (2000° F).

Figure 11. - Replica electron micrographs of hard-drawn W-Re-Hf-C wire tested at various temperatures. X9 000. (Reduced 50 percent in printing.)



(d) After 18.4 hours at 1204° C (2200° F).



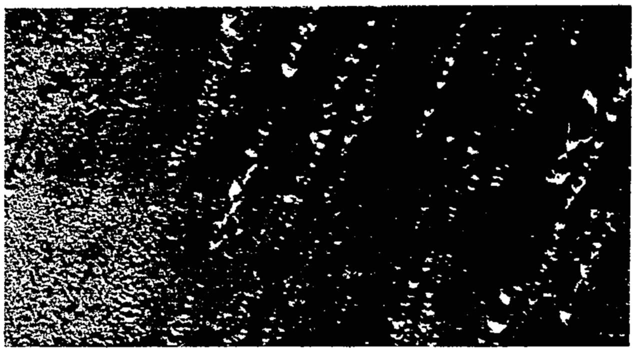
(e) After 365.5 hours at 1204° C (2200° F).

Figure 11. - Concluded.

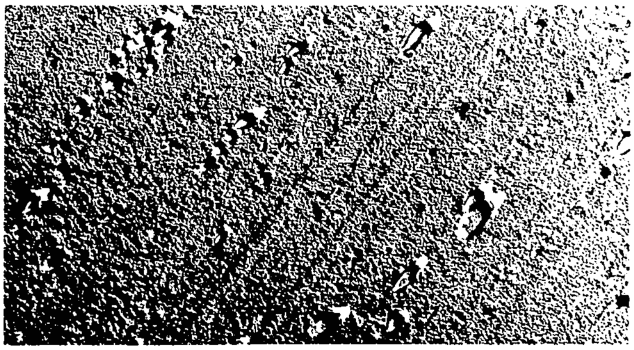
Tantalum-Base Alloy (ASTAR 811C)

Figures 12(a) to (e) are electron photomicrographs of 0.051-centimeter- (0.020-in.-) diameter ASTAR 811C wire exposed to the indicated temperatures and times. The as-drawn structure of the wire is shown in figure 12(a). Pronounced particle alinement is observed. The dispersed particles range in size from 0.015 to 1.0 micrometer. The precipitate particles are believed to be tantalum dimetal carbide, Ta_2C. Increased temperature and time of exposure resulted in coarsening of precipitates and volume-percent increase of precipitates. Major differences were noticed between the periphery and the center portions of the wires exposed to elevated temperatures. Particles of larger size and in greater abundance were observed at the periphery of the wires.

Figures 13(a) to (e) are electron photomicrographs of 0.038-centimeter- (0.015-in.-) diameter ASTAR 811C wire exposed to the indicated temperatures and times. The microstructures observed were similar to those obtained for the larger diameter wire except for the specimen exposed at 1093° C (2000° F) for 338.2 hours, which had a lower particle content than the large-diameter wire.



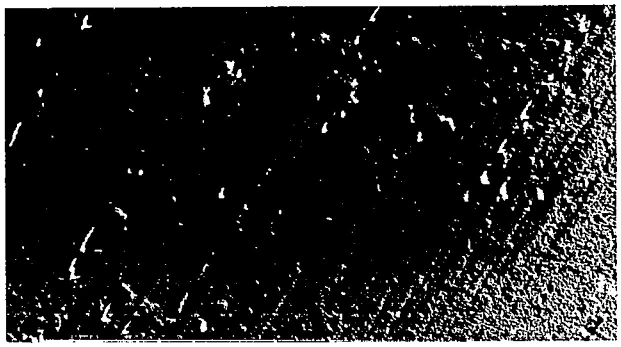
(a) As drawn.



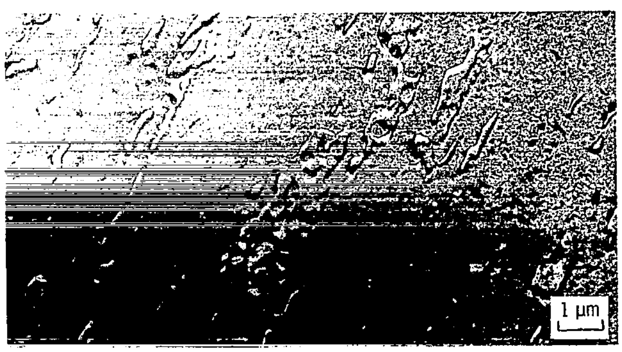
(b) After 7.3 hours at 1093° C (2000° F).

(c) After 338.2 hours at 1093° C (2000° F).

Figure 12. - Replica electron micrographs of 0.051-centimeter- (0.020-in.-) diameter ASTAR 811C wire tested at various temperatures. X12 000. (Reduced 50 percent in printing.)

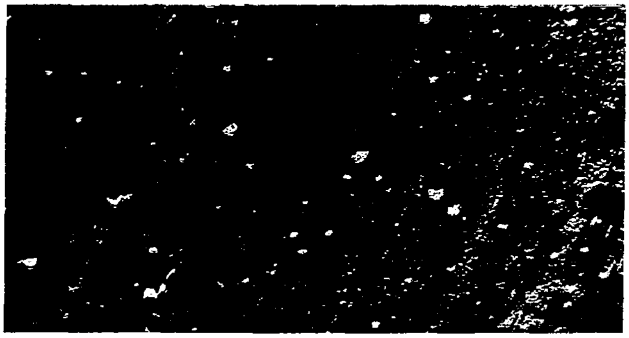


(d) After 10.8 hours at 1204° C (2200° F).

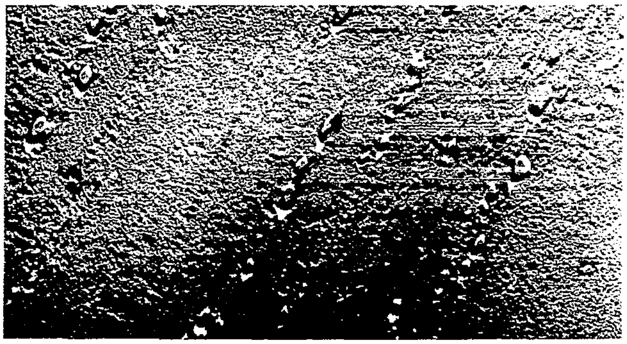


(e) After 166.7 hours at 1204° C (2200° F).

Figure 12. - Concluded.



(a) As drawn.

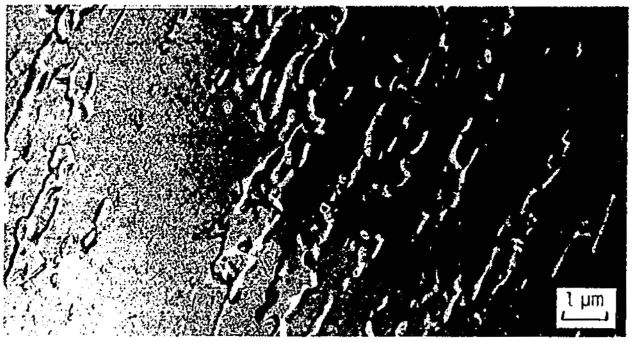


(b) After 14.6 hours at 1093° C (2000° F).

(c) After 338.2 hours at 1093° C (2000° F).

Figure 13. - Replica electron micrographs of 0.038-centimeter- (0.015-in.-) diameter ASTAR 811C wire tested at various temperatures. X12 000. (Reduced 50 percent in printing.)

(d) After 10.2 hours at 1204° C (2200° F).



(e) After 391.9 hours at 1204° C (2200° F).

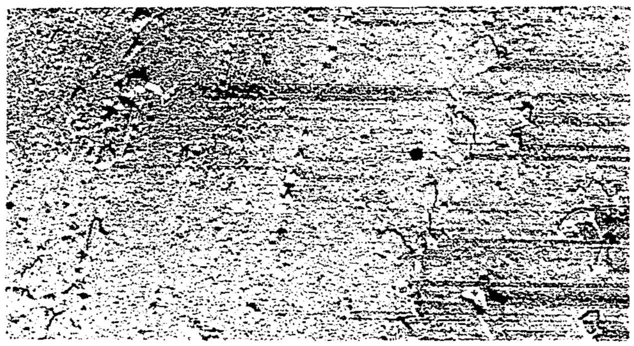
Figure 13. - Concluded.

Columbium-Base Alloy (B-88)

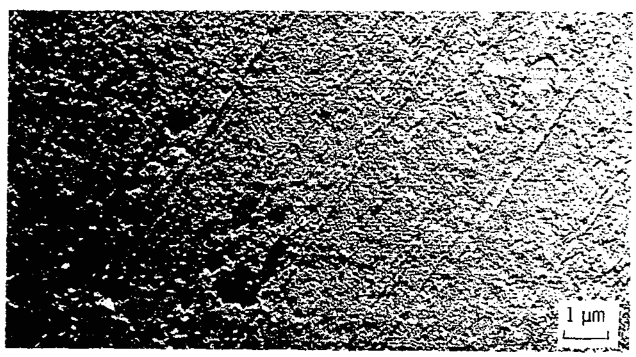
Figure 14(a) is an electron photomicrograph of a 0.051-centimeter- (0.020-in.-) diameter B-88 as-drawn wire. Microporosity resulting from what is assumed to be a preferential etching attack of highly worked wires is observed. The microstructure of a specimen exposed to 1093° C (2000° F) for 4.1 hours is shown in figure 14(b). Particles ranging in size from 0.030 to 2 micrometers are seen. The larger particles had a tendency to aline themselves in the longitudinal direction of the wire. The particles are believed to be the face-centered cubic monocarbide, (Cb, Hf) C_{1-x}. Figure 14(c) is an electron photomicrograph of a wire specimen exposed to 1093° C (2000° F) for 101.3 hours. The particles were slightly larger and more numerous than in the short-time exposure at 1093° C (2000° F). Structures of specimens exposed at 1204° C (2200° F) for 2.6 and 78.5 hours are shown in figures 14(d) and (e).

Figure 15(a) to (e) are electron photomicrographs of 0.038-centimeter- (0.015-in.-) diameter B-88 wire exposed to the indicated temperatures and times. The microstructures were similar to those obtained for the larger diameter wire with the exception that at 1093° C (2000° F) an apparent loss of fibrous structure is observed and much larger subgrains are formed after long time exposure at 1204° C (2200° F).

(a) As drawn.



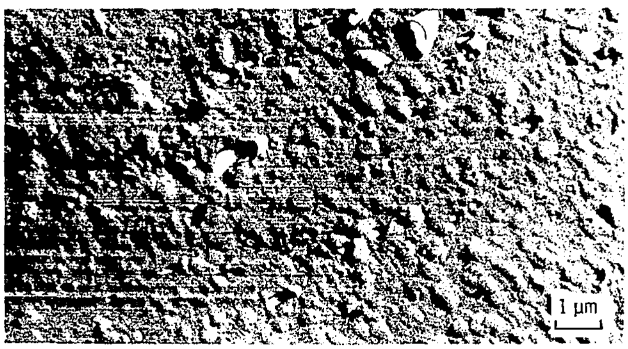
(b) After 4.1 hours at 1093° C (2000° F).



(c) After 101.3 hours at 1093° C (2000° F).

Figure 14. - Replica electron micrographs of 0.051-centimeter- (0.020-in.-) diameter B-88 wire tested at various temperatures. X12 000. (Reduced 50 percent in printing.)

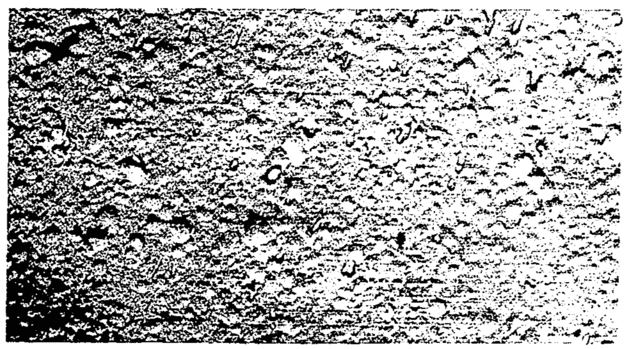
(d) After 2.6 hours at 1204° C (2200° F).



(e) After 78.5 hours at 1204° C (2200° F).

Figure 14. - Concluded.

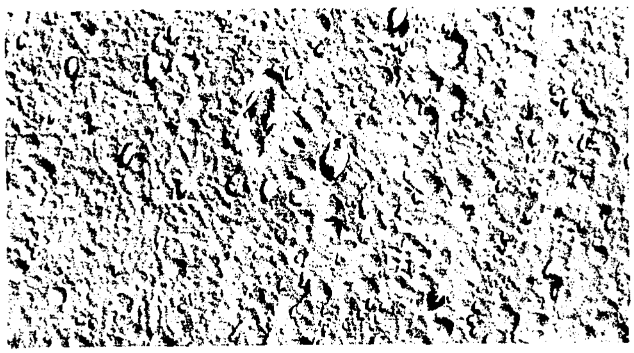
(a) As drawn.



(b) After 44.8 hours at 1093° C (2000° F).

(c) After 199.3 hours at 1093° C (2000° F).

Figure 15. - Replica electron micrographs of 0.038-centimeter- (0.015-in.-) diameter B-88 wire tested at various temperatures. X12 000. (Reduced 50 percent in printing.)



(d) After 25.4 hours at 1204° C (2200° F).

(e) After 224.1 hours at 1204° C (2200° F).

Figure 15. - Concluded.

DISCUSSION

Mechanical Properties

The W-Re-Hf-C wire used in this investigation had a 100-hour rupture strength at 1093° C (2000° F) over twice that of the W - 2-percent-ThO_2 wire which has successfully been utilized to reinforce superalloys (ref. 1). The W-Re-Hf-C wire was found to be the strongest wire material of those tested in stress-rupture at both 1093° and 1204° C (2000° and 2200° F). Table V compares the 100-hour rupture strengths of the wires tested in this investigation with those of the W - 2-percent-ThO_2 wire. This comparison is also shown in figure 16. All of the tungsten alloy wires used in the present investigation were stronger in stress-rupture than the W - 2-percent-ThO_2 wire. The 100-hour rupture strength for the ASTAR 811C wire compares favorably with that of the W - 2-percent-ThO_2 wire while the stress to cause rupture in 100 hours for the columbium-base alloy (B-88) was much lower. However, the densities of the tantalum and columbium alloys are lower than those of the tungsten alloys. Therefore, where the strength-to-density ratio (specific strength) is a criterion for material selection, the

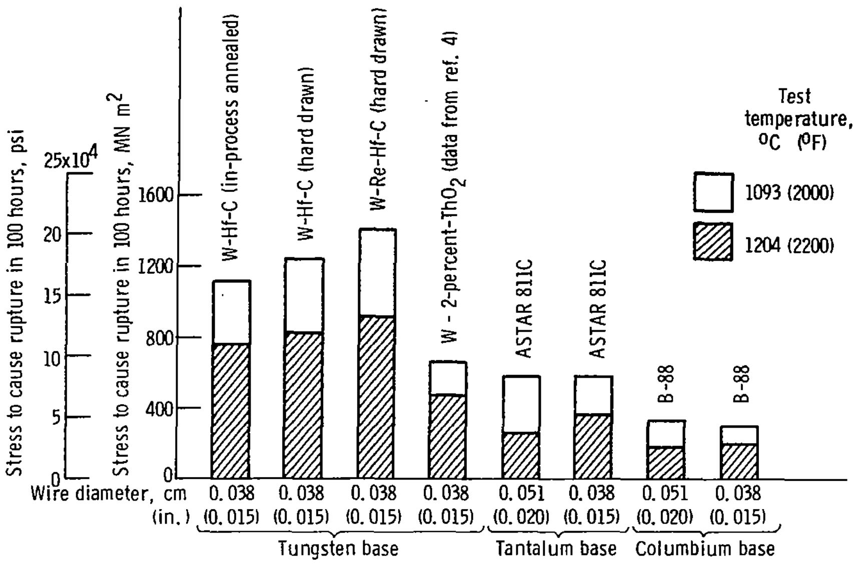


Figure 16. - Stress to cause rupture in 100 hours for refractory metal wires.

tantalum and columbium alloys would compare more favorably with the tungsten alloys. Table V also compares the 100-hour rupture strength divided by the wire density for the wires studied in this investigation with that of W - 2-percent-ThO_2. The strength-to-density values in this report were calculated by using weight-density data and are reported in units of meters (in.). A bar chart showing this comparison is provided in figure 17. The tantalum- and columbium-base wire materials have about the same 100-hour specific rupture strengths as that of the W - 2-percent-ThO_2 wire at 1093° C

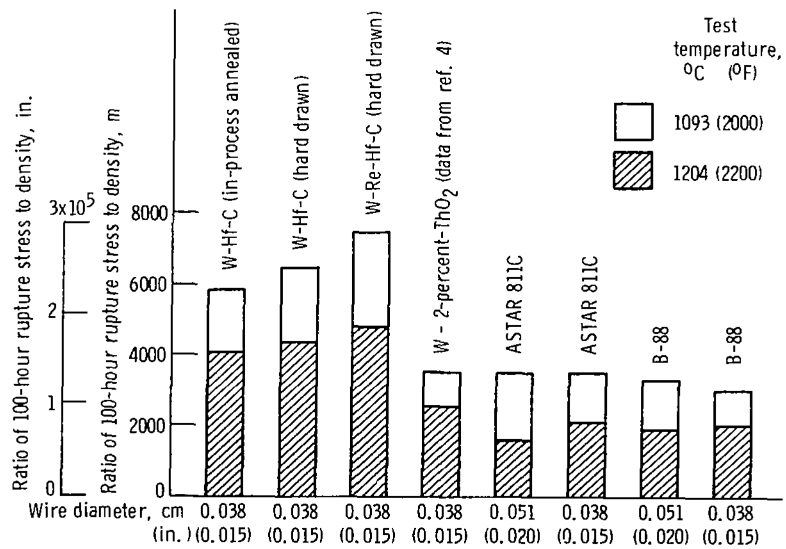


Figure 17. - Ratio of 100-hour rupture strength to density for refractory metal wires.

(2000° F), and they have slightly lower strengths at 1204° C (2200° F). Even when density is taken into account, however, the W-Re-Hf-C and W-Hf-C wires are much superior to the other wire materials.

The ultimate tensile-strength values obtained for the wire materials were found to be much higher than those reported for the same materials in rod, bar, or sheet form. The only unexpected exceptions were the 1093° and 1204° C (2000° and 2200° F) tensile strengths of the B-88 wire, which were lower than the tensile strengths reported for this material in rod form. The ultimate tensile strengths obtained for the wire materials investigated are shown in figure 18. Also shown in figure 18 are the tensile-

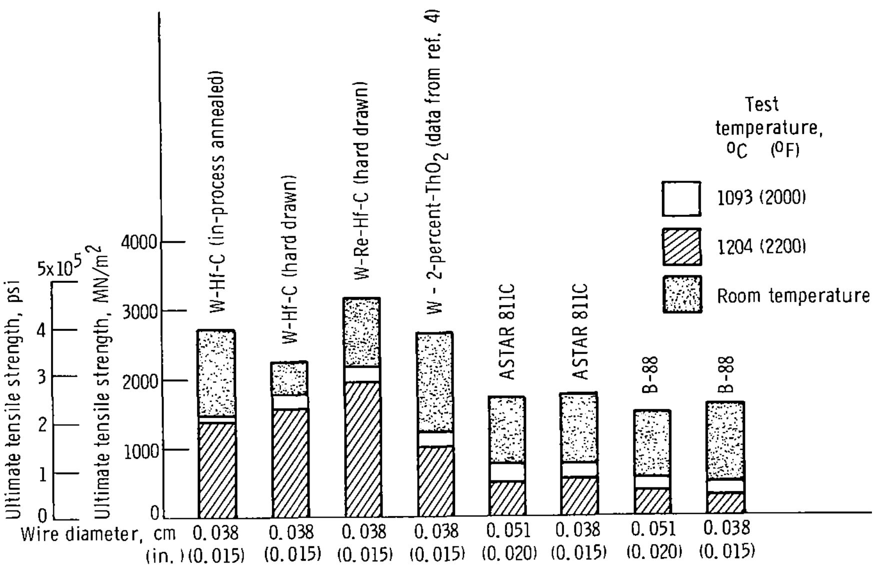


Figure 18. - Ultimate tensile strength of refractory metal wires.

strength values reported in reference 4 for W - 2-percent-ThO_2 wire, which, as stated previously, was successfully used as a reinforcement material in composites reported in reference 1. The tungsten-base alloys had the highest ultimate tensile strengths at all the temperatures investigated.

When density is taken into account, the tantalum- and columbium-base wire materials compare considerably more favorably with the tungsten-base alloys, particularly at room temperature, as indicated in figure 19. At elevated temperatures, however, the tungsten-base alloys have superior specific tensile strengths compared to the other wire materials studied.

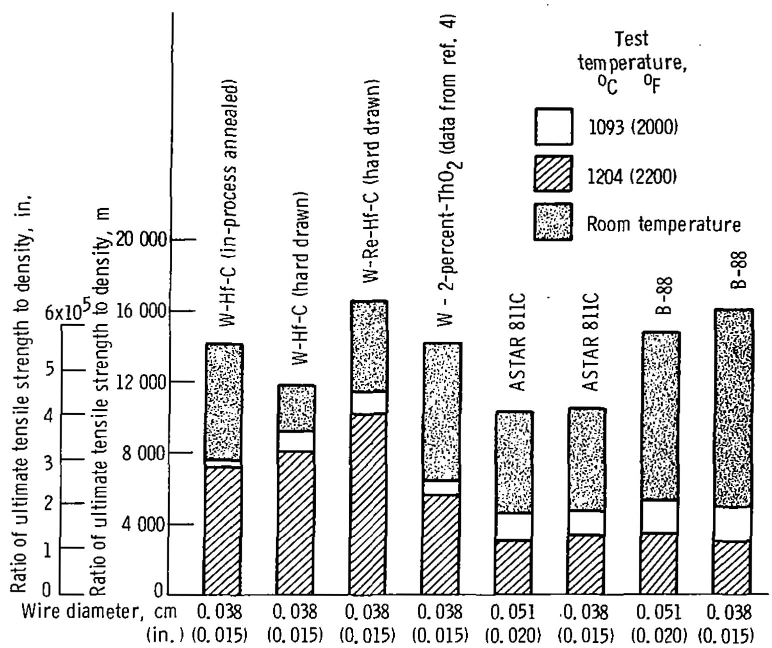


Figure 19. - Ratio of ultimate tensile strength to density of refractory metal wires.

Microstructure

Generally, all wire materials studied had similar microstructural stability and had about the same stabilities in stress rupture, as seen by their equivalent slopes in the plots of stress-to-rupture as a function of time-to-rupture of figures 7 and 8. However, minor concurrent variations in both microstructural and stress-rupture stability were observed for the following few cases. The 0.051-centimeter- (0.020-in.-) diameter ASTAR 811C wire had a steeper slope for stress to rupture against rupture time at 1093° C (2000° F) than did the 0.038-centimeter- (0.015-in.-) diameter wire. At 1093° C (2000° F), the larger diameter ASTAR 811C wire had a less stable microstructure than did the smaller diameter wire, as evidenced by the higher particle content for the 0.051-centimeter- (0.020-in.-) diameter wire for long-time exposure at this temperature. At 1204° C (2200° F), the ASTAR 811C material of both diameters had similar stress-rupture stability and microstructural stability. A difference in stress rupture and microstructural stability was also noted for the B-88 wire material, at both 1093° and 1204° C (2000° and 2200° F). The 0.038-centimeter- (0.015-in.-) diameter B-88 wire was less stable in both stress-rupture and microstructure at both temperatures than the larger diameter wire. At 1093° C (2000° F), the smaller diameter B-88 wire showed an apparent loss of fibrous structure with exposure time, while the larger diameter B-88 wire did not. At 1204° C (2200° F), the 0.038-centimeter- (0.015-in.-)

diameter B-88 wire formed much larger subgrains after long-time exposure than did the larger diameter B-88 wire.

Potential of Refractory Metal Fiber in Superalloy Composites

Refractory metal-alloy wires are of interest for fiber reinforcement of superalloy matrix materials for use between 1093° and 1204° C (2000° and 2200° F). Previous experimental work at Lewis (refs. 1 and 2) has shown that composites of superalloys reinforced with available refractory metal wires can be produced that have stress-rupture strengths superior to conventional superalloys at use temperatures of 1093° and 1204° C (2000° and 2200° F). Composite strength was found to be dependent on fiber properties and on the compatibility of the fiber with the matrix. The stress-rupture properties of the composite could be approximated if the fiber stress-rupture properties were known. One of the objectives of this investigation was to determine the potential of the wire materials investigated as reinforcing fibers for superalloy composites.

Tensile strength. - The potential ultimate tensile strengths of superalloy composites containing wires studied in this investigation were calculated for 1093° C (2000° F) by using the rule-of-mixtures relation. It was assumed that the composite contained 70 volume percent wire and that negligible reaction would occur between the wire and matrix during fabrication or exposure for short times at 1093° C (2000° F). The strongest wire was selected from each wire alloy group. Figures 20 and 21 show the predicted

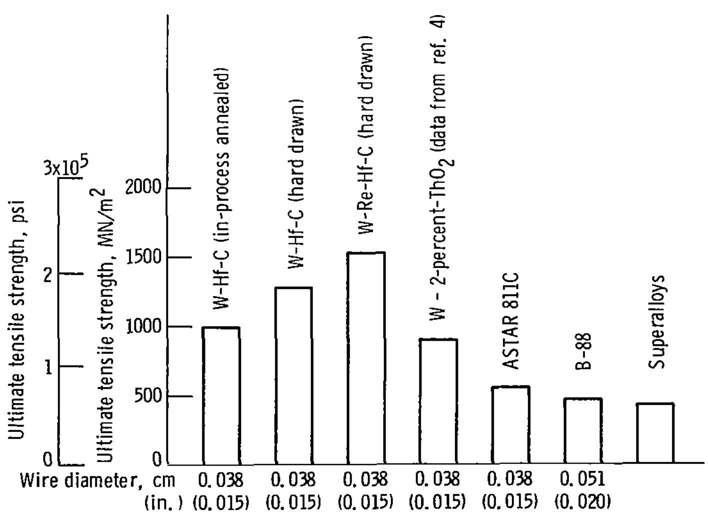


Figure 20. - Potential ultimate tensile strengths of refractory metal wire and superalloy composites at 1093° C (2000° F). Fiber content of composite, 70 volume percent.

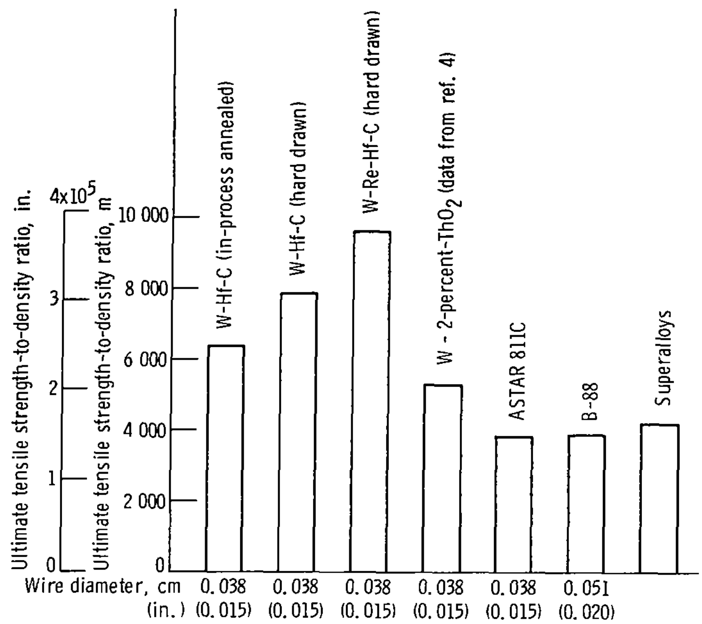


Figure 21. - Potential ultimate tensile strength-to-density ratio of wire-and-superalloy composites at 1093° C (2000° F). Fiber content of composite, 70 volume percent.

1093° C (2000° F) ultimate tensile strength and the specific ultimate tensile strength of composites compared with those of the strongest superalloys. An ultimate tensile strength of over 1380 meganewtons per square meter (200 000 psi) may be projected for a composite containing 70 volume percent W-Re-Hf-C wire. The strongest superalloys have an ultimate tensile strength of approximately 350 meganewtons per square meter (50 000 psi) at this temperature.

Tensile strength-to-density ratio. - The tungsten-alloy wire composite appears to offer the most potential, even when density is taken into consideration, as shown in figure 21. The W-Re-Hf-C wire composite has a potential specific ultimate tensile strength of 9630 meters (379 000 in.) at 1093° C (2000° F) compared to 4240 meters (167 000 in.) for the strongest superalloys. The superalloys have a specific ultimate tensile strength of 9630 meters (379 000 in.) at 871° to 927° C (1600° to 1700° F). The potential specific ultimate tensile strength of the W-Re-Hf-C wire reinforced superalloy composite represents a use-temperature advantage of 165° to 222° C (300° to 400° F) over superalloys. The ASTAR 811C and B-88 wire reinforced superalloy composites have potential ultimate tensile strengths equivalent to those of the strongest superalloys at 1093° C (2000° F).

Stress-rupture strength. - The potential 100-hour rupture strengths at 1093° C (2000° F) were also determined for superalloy composites containing 70 volume percent of refractory metal alloy wire. The potential rupture strengths of the composites were determined for two conditions. The first condition assumed that reaction with the wire and matrix does not occur, which would represent a composite system in which the matrix is insoluble in the wire or in which the wires are coated with a diffusion barrier. The second condition assumed that reaction between the matrix and wire does occur but that 80 percent of the wire strength is retained after exposure at 1093° C (2000° F) for 100 hours. Seventy-four percent of the wire strength was actually retained in stress-rupture for the W - 2-percent-ThO_2 composites investigated in reference 1. When tungsten lamp filament wire was used as a reinforcement, 90 percent of the wire strength in stress-rupture was retained after exposure at 1093° C (2000° F), as reported in reference 2. The 80-percent value used in our calculations thus appears reasonable. The potential 100-hour rupture strength for wire-reinforced superalloy composites is given in figure 22. Also shown in figure 22 are the actual 100-hour rupture strengths

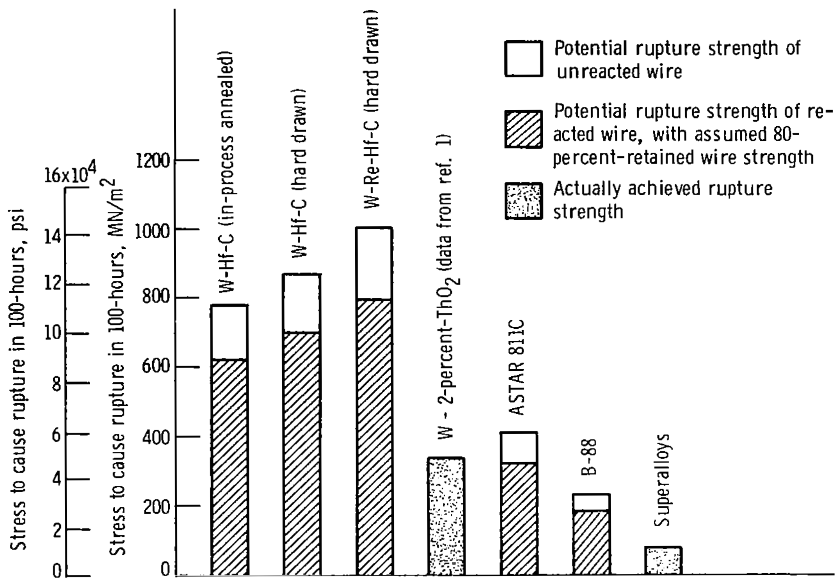


Figure 22. - Potential 100-hour rupture strengths of wire-superalloy composites at 1093° C (2000° F). Fiber content of composites, 70 volume percent.

for superalloys and for a W - 2-percent-ThO_2 wire-and-superalloy composite which was investigated in a previous program at Lewis and which is also reported in reference 1. A 100-hour rupture strength at 1093° C (2000° F) of 993 meganewtons per square meter (144 000 psi) might be obtained for a composite containing W-Re-Hf-C wire if reaction between the wire and superalloy matrix could be avoided. Composites containing either ASTAR 811C or B-88 as a reinforcement would have a 100-hour rupture strength much lower than that obtained with W-Re-Hf-C or W-Hf-C wire even if reaction could be avoided. The 100-hour rupture strength for all the potential wire material would be greater than that obtained for the strongest superalloys at this temperature. If it is assured that reaction with the wire cannot be prevented, the value for the 100-hour rupture life of the composite would be approximated by that shown in figure 22. The W-Re-Hf-C wire composite would have a 100-hour rupture strength of 793 meganewtons per square meter (115 000 psi) compared to a value of 340 meganewtons per square meter (49 000 psi) reported in reference 1 for a tungsten - 2-percent-thoria wire composite. Composites reinforced with ASTAR 811C or B-88 wire would have 100-hour rupture strengths lower than those obtainable for the W-Re-Hf-C or W-Hf-C wire composites but higher than those obtained for superalloys. A potential increase in the 100-hour rupture strength of over 100 percent exists for composites containing W-Re-Hf-C wire as compared with the composites produced in reference 1, which contained tungsten - 2-percent-thoria wire. The potential 100-hour rupture strength of the W-Re-Hf-C wire composite is also approximately 10 times that of the strongest conventional superalloys at this temperature. The composite has a 100-hour stress for rupture value at 1093° C (2000° F) equivalent to that of conventional superalloys at 649° C (1200° F), or a 444° C (800° F) use-temperature advantage.

Stress-rupture strength-to-density ratio. - The densities of the composite materials, however, are much greater than those of superalloys and should be taken into consideration for applications such as turbojet engines where weight is important. The potential 100-hour specific rupture strength for the wire-superalloy composites is presented in figure 23. The two assumptions (unreacted wire and reacted wire) used in plotting figure 22 were also used to construct this figure. When density is taken into consideration, the tantalum- and columbium-base wire materials appear more promising. The potential specific 100-hour rupture strength for the W-Re-Hf-C wire composite, if reaction is assumed, is 5030 meters (198 000 in.) as compared to 2110 meters (83 000 in.) for

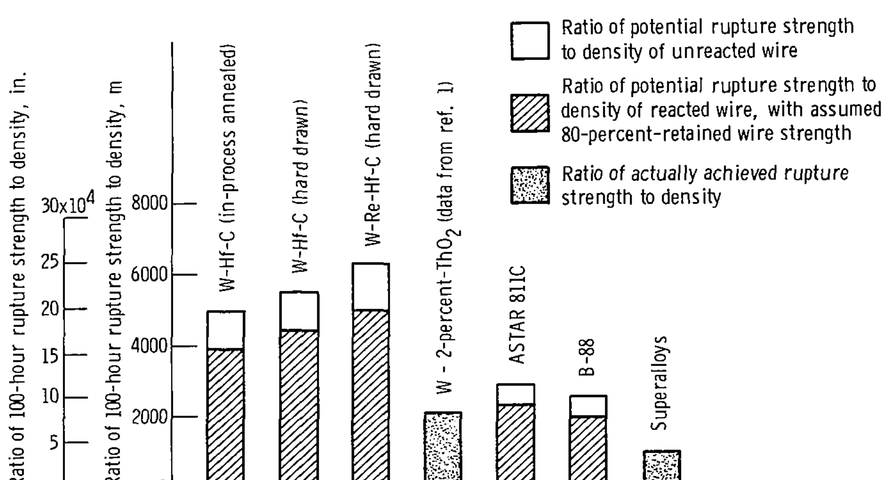


Figure 23. - Potential 100-hour rupture strength to density ratios of wire-superalloy composites at 1093° C (2000° F). Fiber content of composites, 70 volume percent.

the tungsten - 2-percent-thoria wire and superalloy composite reported in reference 1 and 1000 meters (39 000 in.) for the strongest superalloys. The W-Re-Hf-C composite has a potential 100-hour specific rupture strength at 1093° C (2000° F) equivalent to that of conventional superalloys at 871° C (1600° F), or a 222° C (400° F) use-temperature advantage. The ASTAR 811C and B-88 wire composites are equivalent to the tungsten - 2-percent-thoria wire composite on a strength-to-density basis for rupture in 100 hours at 1093° C (2000° F) and have a use-temperature advantage of 111° C (200° F) over the strongest conventional superalloys.

The tungsten - 2-percent-thoria wire and superalloy composite has previously been shown to have (ref. 1) a potential 111° C (200° F) turbine-blade use-temperature advantage over superalloys. The composite contains 70 volume percent fibers, however, and is quite dense. This composite density of 16.1 grams per cubic centimeter (0.58 lb/in.^{3}) is considerably above the 8.30 to 9.13 grams per cubic centimeter (0.30 to 0.33 lb/in.^{3}) of conventional superalloys used for turbine blades. The superior stress-to-density properties of the composite can be used to increase the turbine-blade operating temperature by 111° C (200° F) without increasing blade weight, with an appropriate hollow blade design. However, if a direct substitution of a fixed-external-geometry solid-blade design is used, the 111° C (200° F) increase in temperature for the composite blade will be achieved with about $1\frac{1}{2}$ times as heavy a blade. The density penalty can be reduced for substitutional solid blades by using stronger tungsten alloy fibers and reducing the fiber content of the composite or by using lower density fibers. Figure 24 is a plot of the potential densities for composites having a 100-hour specific rupture strength of 2100 meters (83 000 in.) at 1093° C (2000° F) and the specific 100-hour rupture strength actually obtained for composites containing 70 volume percent of W - 2-percent-thoria

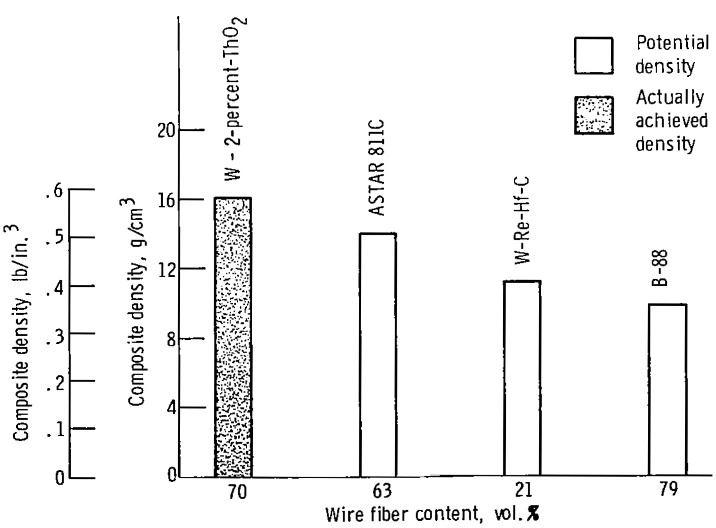


Figure 24. - Potential densities of composites having a 100-hour specific rupture strength of 2100 meters (83 000 in.) at 1093° C (2000° F). Reacted wire with 80-percent-retained strength assumed.

fibers. Fiber reaction is assumed, so that 80 percent of the fiber properties are retained after exposure for 100-hours at 1093° C (2000° F). The fiber content necessary to obtain this rupture strength was determined by the rule-of-mixtures relation assuming that the fibers carry all the load. It is also indicated in the plot. The tungsten - 2-percent-thoria fiber composite has a density of 16.1 grams per cubic centimeter (0.58 lb/in.^{3}). By use of the B-88 fibers, the density of the composite can be lowered to 9.8 grams per cubic centimeter (0.35 lb/in.^{3}) while maintaining the same specific rupture strength for 100 hours as obtained for the tungsten - 2-percent-thoria fiber composites.

Based on the potential composite strengths and densities indicated above, it may be possible to achieve a B-88 columbium alloy wire reinforced superalloy which has the strength-to-density ratio required for 1093° C (2000° F) turbine-blade operation. A solid blade of this composite would permit a 111° C (200° F) service-temperature increase over conventional superalloys, with only a 10- to 18-percent weight increase.

SUMMARY OF RESULTS

The tensile properties of refractory-metal alloy wires of W-Re-Hf-C, W-Hf-C, ASTAR 811C, and B-88 were determined at room temperature, 1093° C (2000° F), and 1204° C (2200° F). Stress-rupture properties were also determined at 1093° C (2000° F) and 1204° C (2200° F) for rupture times up to 100 hours. The rupture properties were correlated to microstructure, and the potential of the wires as a reinforcement for superalloys was determined. The following results were obtained:

1. Tungsten-base alloy wire had a 100-hour rupture strength over twice that of either the tantalum-base wire (ASTAR 811C) or the columbium-base wire (B-88). The W-Re-Hf-C wire had the highest 100-hour rupture strength at both 1093° and 1204° C (2000° and 2200° F), with 1410 and 910 meganewtons per square meter (205 000 and 132 000 psi), respectively. Even when density was taken into consideration, the tungsten-base alloy wire materials were stronger in stress-rupture than either the tantalum- or columbium-base alloy wire materials investigated. Specific 100-hour rupture strengths of 7440 meters (293 000 in.) at 1093° C (2000° F) and 4801 meters (189 000 in.) at 1204° C (2200° F) were obtained for W-Re-Hf-C wire.

2. The ultimate tensile strength values obtained for the wire materials at room temperature, 1093° C (2000° F), and 1204° C (2200° F) were much higher than those reported for rod, bar, or sheet forms of the materials, except for the B-88 wire material.

3. Of the several refractory alloy materials tested, the tungsten-base alloy wire materials studied had the highest ultimate tensile strengths at 1093° C (2000° F) and 1204° C (2200° F). Ultimate tensile strengths of 2170 meganewtons per square meter

(314 000 psi) for W-Re-Hf-C tested at 1093° C (2000° F) and 1440 meganewtons per square meter (281 000 psi) for W-Re-Hf-C wire tested at 1204° C (2200° F) were obtained.

4. All of the wire materials investigated were microstructurally stable with time at temperature. Only minor differences in microstructure were observed. Where minor differences in microstructure were observed, there was a corresponding minor difference in the slope of the rupture stress against time curves.

CONCLUDING REMARKS

The attractive strengths indicated for these wires offer the potential for increased strength if they can be applied to metallic composites. The strength of superalloy matrix composites reinforced with these refractory alloy fibers were calculated. The following potentialities may be realized if these composites can be fabricated:

It may be possible to produce W-Re-Hf-C fiber reinforced nickel- or cobalt-base superalloys with over four times the tensile strength and up to ten times the 100-hour rupture strength at 1093° C (2000° F) of the strongest conventional superalloys. Such a composite material may be applied to hollow turbine blades for operating temperatures in the 1093° to 1204° C (2000° to 2200° F) range.

It may be possible to produce B-88 columbium alloy fiber and superalloy composites with a specific 100-hour rupture strength adequate for turbine blade service at 1093° C (2000° F). A solid turbine blade of B-88 and superalloy composite would be 10 to 18 percent heavier than a conventional superalloy blade but would permit a 111° C (200° F) increase in operating temperature.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 4, 1972,
134-03.

REFERENCES

1. Petrasek, Donald W.; and Signorelli, Robert A.: Preliminary Evaluation of Tungsten Alloy Fiber - Nickel-Base Alloy Composites for Turbojet Engine Applications. NASA TN D-5575, 1970.

2. Petrasek, Donald W.; Signorelli, Robert A.; and Weeton, John W.: Refractory-Metal-Fiber-Nickel-Base-Alloy Composites for Use at High Temperatures. NASA TN D-4787, 1968.

3. McDanels, David L.; and Signorelli, Robert A.: Stress-Rupture Properties of Tungsten-Wire from 1200° to 2500° F. NASA TN D-3467, 1966.

4. Petrasek, Donald W.; and Signorelli, Robert A.: Stress-Rupture and Tensile Properties of Refractory-Metal Wires at 2000° and 2200° F (1093° and 1204° C). NASA TN D-5139, 1969.

TABLE I. - CHEMICAL ANALYSIS OF MATERIAL COMPOSITION

Wire material	Component element, wt. %							
	C	Cb	Hf	N	O	Re	Ta	W
W-Hf-C (hard drawn)	0.042		0.33					Balance
W-Hf-C (in-process annealed)	.030		.37					Balance
W-Re-Hf-C	.021		.38			4.1		Balance
ASTAR 811C	.027		.91	0.0026	0.0058	1.13	Balance	8.2
B-88	.058	Balance	1.94	.0029	.010			28.3

TABLE II. - TENSILE PROPERTIES OF REFRACTORY METAL WIRES

Wire material	Wire diameter		Test temperature		Ultimate tensile strength		Percent elongation in 2.5 cm (1 in.)	Reduction in area, percent
	cm	in.	^{o}C	^{o}F	MN/m^2	psi		
W-Hf-C (in-process annealed)	0.038	0.015	(a)	(a)	2700	392 000	5.4	21.1
			1093	2000	1430	207 000	---	67.8
			1204	2200	1390	201 000	---	70.9
W-Hf-C (hard drawn)	0.038	0.015	(a)	(a)	2250	326 000	2.8	1.9
			1093	2000	1740	253 000	---	44.2
			1204	2200	1540	224 000	---	46.9
W-Re-Hf-C (hard drawn)	0.038	0.015	(a)	(a)	3160	458 000	4.8	27.5
			1093	2000	2160	314 000	---	24.7
			1204	2200	1940	281 000	---	37.6
ASTAR 811C	0.051	0.020	(a)	(a)	1700	247 000	6.9	51.0
			1093	2000	744	108 000	---	80.8
			1204	2200	490	71 000	---	89.8
	0.038	0.015	(a)	(a)	1740	253 000	5.3	42.9
			1093	2000	779	113 000	---	66.4
			1204	2200	550	80 000	---	66.9
B-88	0.051	0.020	(a)	(a)	1480	215 000	4.8	26.5
			1093	2000	530	77 000	---	87.4
			1204	2200	350	50 000	---	97.9
	0.038	0.015	(a)	(a)	1620	235 000	7.7	54.8
			1093	2000	490	71 000	---	94.5
			1204	2200	310	45 000	---	95.7
W - 2-percent-ThO_2 (data from ref. 4)	0.038	0.015	(a)	(a)	2650	384 000	5.5	14.2
			1093	2000	1190	173 000	---	50.2
			1204	2200	1030	150 000	---	51.0

[a]Room temperature.

TABLE III. - STRESS-RUPTURE PROPERTIES OF WIRE MATERIALS

(a) Tungsten-base alloys

Wire material	Wire diameter		Test temperature		Stress		Rupture time, hr	Reduction in area, percent
	cm	in.	°C	°F	MN/m²	psi		
W-Hf-C (thermally annealed during drawing)	0.038	0.015	1093	2000	1300	189 000	4.4	44.2
					1290	187 000	10.3	58.4
					1230	178 000	21.1	23.2
					1210	175 000	19.1	35.0
					1150	167 000	61.5	44.5
					1110	161 000	108.5	18.0
	0.038	0.015	1204	2200	918	133 000	28.3	15.3
					841	122 000	42.9	21.9
					765	111 000	104.3	11.5
					689	100 000	188.4	28.5
W-Hf-C (hard drawn)	0.038	0.015	1093	2000	1310	190 000	17.7	44.2
					1240	180 000	139.4	37.0
					1230	178 000	88.6	22.6
					1210	175 000	262.0	57.3
					1100	160 000	(a)	----
	0.038	0.015	1204	2200	1170	170 000	6.0	29.4
					1140	165 000	4.3	30.6
					1100	160 000	11.1	20.2
					1040	150 000	22.5	24.9
					965	140 000	18.6	20.2
					896	130 000	37.4	16.6
					827	120 000	63.0	22.6
					793	115 000	74.3	17.8
					758	110 000	334.1	50.2
					689	100 000	329.6	65.8
W-Re-Hf-C (hard drawn)	0.038	0.015	1093	2000	1590	230 000	15.6	15.7
					1520	220 000	36.2	19.5
					1480	215 000	42.8	34.0
					1450	210 000	72.1	27.1
					1380	200 000	442.6	34.7
					1310	190 000	104.2	16.7
					1240	180 000	522.3	37.3
	0.038	0.015	1204	2200	1140	165 000	14.4	32.0
					1040	150 000	18.4	43.2
					965	140 000	39.7	23.0
					896	130 000	49.8	32.8
					862	125 000	365.5	33.7
					827	120 000	345.5	44.3
					793	115 000	342.2	43.2

[a]Test stopped at 233.4 hr.

TABLE III. - Concluded. STRESS-RUPTURE PROPERTIES OF WIRE MATERIALS

(b) Tantalum-base alloy

Wire material	Wire diameter		Test temperature		Stress		Rupture time, hr	Reduction in area, percent
	cm	in.	^{o}C	^{o}F	MN/m^2	psi		
ASTAR 811C	0.051	0.020	1093	2000	690	100 000	7.3	17.5
					620	90 000	68.5	8.7
					590	85 000	43.0	7.0
					520	75 000	338.2	3.8
	0.038	0.015	1093	2000	620	90 000	14.6	29.8
					590	85 000	94.6	4.2
					570	82 000	19.1	19.3
					570	82 000	162.8	6.6
					550	80 000	338.2	7.4
					550	80 000	(b)	----
	0.051	0.020	1204	2200	350	50 000	10.8	8.8
					310	45 000	28.5	9.7
					280	40 000	78.3	8.3
					240	35 000	166.7	7.3
	0.038	0.015	1204	2200	520	75 000	10.2	15.3
					480	70 000	14.7	10.3
					410	60 000	45.4	5.2
					380	55 000	20.1	6.5
					350	50 000	62.7	2.8
					310	45 000	391.9	<1.0

(c) Columbium-base alloy

Wire material	Wire diameter		Test temperature		Stress		Rupture time, hr	Reduction in area, percent
	cm	in.	^{o}C	^{o}F	MN/m^2	psi		
B-88	0.051	0.020	1093	2000	380	55 000	4.1	32.8
					370	53 000	37.1	15.8
					350	50 000	101.3	18.6
					310	45 000	102.1	16.6
	0.038	0.015	1093	2000	350	50 000	44.8	22.1
					310	45 000	55.4	23.3
					280	40 000	199.3	20.7
	0.051	0.020	1204	2200	280	40 000	2.6	34.7
					240	35 000	14.4	39.9
					210	30 000	78.5	20.9
	0.038	0.015	1204	2200	240	35 000	25.4	32.0
					210	30 000	86.8	28.6
					170	25 000	224.1	26.1

[b]Test stopped at 348.9 hr.

TABLE IV. - SUMMARY OF WIRE MICROSTRUCTURE OBSERVATIONS AS FUNCTIONS OF EXPOSURE TIME AND TEMPERATURE

Wire material	Condition				
	As drawn	Exposed at 1093° C (2000° F)		Exposed at 1204° C (2200° F)	
		Short time, $<$50 hr	Long time, $>$80 hr	Short time, $<$50 hr	Long time, $>$80 hr
W-Hf-C (hard drawn)	Heavily worked elongated grains; HfC particles, 0.015 to 0.040 micrometer in size	---------------	Grain-width increase and subgrain formation	Grain-width increase	Grain-width increase
W-Re-Hf-C (hard drawn)	Heavily worked elongated grains; small particles, 0.010 to 0.120 micrometer in size	Structure similar to as-drawn condition	Grain-width increase and some subgrain formation	Grain-width increase and subgrain formation	Grain-width increase
W-Hf-C (annealed during drawing)	Heavily worked elongated grains; small particles of HfC, 0.030 to 0.100 micrometer in size	Structure similar to as-drawn condition	Grain-width increase	Grain-width increase and subgrain formation	Formation of long wide grains
ASTAR 811C	Pronounced particle alinement; particles range in size from 0.015 to 1.0 micrometer	Structure similar to as-drawn condition	Particle coarsening; higher particle content than for short-time exposure	Particle coarsening	Particle coarsening and higher particle content than for short-time exposure; apparent loss of fibrous structure
B-88	Heavily worked elongated grains; particles range in size from 0.030 to 2 micrometers	Particle coarsening	Higher particle content than for short-time exposure; particle coarsening	Particle-content increase and subgrain formation	Particle coarsening and subgrain formation

TABLE V. - 100-HOUR RUPTURE STRENGTH AND SPECIFIC 100-HOUR RUPTURE STRENGTH

OF REFRACTORY METAL WIRES AT 1093° AND 1204° C (2000° AND 2200° F)

(a) Test temperature, 1093° C (2000° F)

Wire material	Approximate wire density		Wire diameter		100-Hour rupture strength		100-Hour rupture strength-to-density	
	gm/cm^3	$lb/in.^3$	cm	in.	MN/m^2	psi	m	in.
W-Hf-C (hard drawn)	19.37	0.7	0.038	0.015	1240	180 000	6450	257 000
W-Re-Hf-C (hard drawn)	19.37	0.7	0.038	0.015	1410	205 000	7440	293 000
W-Hf-C (in-process annealed)	19.37	0.7	0.038	0.015	1110	161 000	5840	230 000
ASTAR 811C	16.9	0.61	0.051	0.020	580	84 000	3500	138 000
			0.038	0.015	580	84 000	3500	138 000
B-88	10.3	0.373	0.051	0.020	330	48 000	3280	129 000
			0.038	0.015	300	44 000	3000	118 000
W - 2-percent-ThO_2 (data from ref. 4)	18.91	0.68	0.038	0.015	660	96 000	3560	141 000
(b) Test temperature, 1204° C (2200° F)								
W-Hf-C (hard drawn)	19.37	0.7	0.038	0.015	827	120 000	4340	171 000
W-Re-Hf-C (hard drawn)	19.37	0.7	0.038	0.015	910	132 000	4800	189 000
W-Hf-C (in-process annealed)	19.37	0.7	0.038	0.015	765	111 000	4040	159 000
ASTAR 811C	16.9	0.61	0.051	0.020	260	38 000	1600	62 000
			0.038	0.015	355	51 500	2100	84 000
B-88	10.3	0.373	0.051	0.020	190	28 000	1900	75 000
			0.038	0.015	200	29 000	2000	78 000
W - 2-percent-ThO_2 (data from ref. 4)	18.91	0.68	0.038	0.015	480	69 000	2570	101 000

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