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ELEVATED-TEMPERATURE  
TENSILE PROPERTIES OF ALLOYED  
TUNGSTEN FIBER COMPOSITES

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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# ELEVATED-TEMPERATURE TENSILE PROPERTIES OF ALLOYED TUNGSTEN FIBER COMPOSITES

by Donald W. Petrusek

Lewis Research Center

*Start P2*

## SUMMARY

The effects of selected alloying elements on the elevated temperature tensile properties of tungsten fiber reinforced composites were studied.

Composites were made of copper, copper-2 percent chromium and copper-10 percent nickel reinforced with various volume percents of uniaxially oriented tungsten fibers. The composites were tested in tension at temperatures up to 1800<sup>0</sup> F. A comparison of the elevated-temperature tensile properties of tungsten fiber - copper alloy composites, representing soluble systems, was made with tungsten fiber - copper composites, representing a mutually insoluble system. The effects of alloying on the elevated-temperature tensile properties of tungsten fiber reinforced composites was also studied. *end*

A linear relation existed at elevated temperatures between tensile strength and volume percent fiber content for all the systems investigated. The copper alloy composites were weaker in tension at high volume percent fiber contents than copper composites in which alloying with the fiber did not occur. The tensile strength of the alloyed tungsten fiber decreased with increasing penetration of the alloying element into the tungsten fiber.

## INTRODUCTION

The technique of combining strong fibers with relatively weak matrix materials so that the fibers are load carrying members has been utilized for many years in the reinforcement of plastics with glass fibers. This type of strengthening is currently being extended to include the reinforcement of metals with metallic fibers.

Investigations of the room-temperature tensile properties of metal-fiber-reinforced-metallic composites have been numerous (refs. 1 to 11), but the study of tensile prop-

erties at elevated temperatures has been limited.

In previous work done at the Lewis Research Center (ref. 1) composites consisting of mutually insoluble constituents were investigated. Composites were made of copper reinforced with uniaxially oriented tungsten fibers. The stress-strain behavior and tensile properties of the composites were related to the tensile properties of the base materials. The tensile strength of the composite was directly proportional to the volume percent of tungsten fiber present, and the full strength of the fiber was realized.

Few metal fiber - metal matrix systems exist that are mutually insoluble, and those that do exist are not generally practical. An extension of this work was an investigation (ref. 2) of the effects of alloying on the room-temperature properties of fiber-reinforced composites. Composites were made with tungsten fibers and copper binary alloys containing elements having varying solubility in tungsten as the matrix material. The composites were tested in tension at room temperature, and a microstructural study was made to determine the types of reactions occurring at the matrix-fiber interface. The mechanical properties of the copper alloy-tungsten fiber composites studied were reduced when alloying with the tungsten fibers occurred. Several of the composite systems tested, however, showed little reduction in tensile strength relative to composites made from the insoluble materials, copper and tungsten. Alloying additions to copper such as nickel, which formed brittle phase zones, or recrystallized zones, with the tungsten fiber caused the poorest tensile properties because of the brittleness of the fiber-alloy zone and the notch sensitivity of the fiber. Elements such as chromium, which formed ductile alloy zones with the fiber, showed the least reduction in tensile properties.

Since the notch sensitivity of materials decreases and the ductilities of materials increase with temperature, the elevated-temperature properties of composites with brittle alloy zones may be improved relative to those obtained at room temperature.

Alloying elements were studied, which caused the formation of ductile and brittle reaction zones with the fiber at room temperature, to determine their effect on the tensile properties of composites at elevated temperatures.

Copper binary alloys were selected to represent severely damaging and slightly damaging matrices. Chromium additions to a copper matrix caused the least damage to the fiber and resulted in the formation of a ductile fiber reaction zone (ref. 2). Nickel additions to the copper matrix caused the most damage to the fiber and formed a brittle recrystallized fiber reaction zone. The elevated-temperature tensile properties of these copper alloy matrix composites were compared with those of pure copper matrix composites in which fiber reaction zones did not form.

*Start* → Composites were made of <sup>com</sup>copper, <sup>com</sup>copper-2 atomic percent <sup>com</sup>chromium and <sup>com</sup>copper-10 atomic percent <sup>com</sup>nickel reinforced with uniaxially oriented tungsten fibers by a liquid-phase infiltration technique. The composites were tested in tension at temperatures up to 1800° F. Elongation and reduction in area measurements were made. A metallo- <sup>p.3</sup>

graphic study to determine the type of reaction that occurred at the matrix-fiber interface and to measure the depth of penetration of the alloying element into the tungsten fiber was also conducted.

## MATERIALS, APPARATUS, AND PROCEDURE

### Fibers

Commercially pure tungsten wires (General Electric type 218CS) 0.005 inch in diameter were used as the reinforcing fiber material for the composites.

### Infiltrants or Binder Materials

High-purity (oxygen-free, high-conductivity) copper (99.99 percent Cu) was used as the matrix material because copper is insoluble in the tungsten fibers. Copper binary alloys containing either 2 atomic percent chromium or 10 atomic percent nickel were selected as matrices whose alloying elements were soluble in tungsten. Thus, any change in properties of a tungsten fiber reinforced composite using a copper alloy as a matrix relative to using copper as a matrix would be due to the alloying addition to the copper.

### Specimen Preparation

Bundles of 6-inch-long tungsten wires were cleaned to remove surface films and oxides by immersing them in a hot, saturated solution of sodium peroxide and water, followed by a rinsing in distilled water, an immersing in a boiling solution of ammonia and water, and another rinsing in distilled water. The wires were then inserted into ceramic tubes so that the tubes contained wires ranging in volume percent from 50 to 70. For infiltration of the tungsten wires, the ceramic tube was placed in a closed-end quartz tube with some of the copper or copper alloy material on top of the wires. The entire assembly was placed in a resistance-heated vacuum furnace and held at 2200° F for 1 hour. This method assured axial alignment of the fibers to the tensile axis. p. 4

After infiltration, the specimens were removed from the ceramic tubes and ground into approximately 1/8-inch-diameter button-head type tensile specimens.

## Test Procedure

Room-temperature and elevated-temperature tests were made on the composites using an Instron tensile testing machine. A constant cross-head speed of 0.10 inch per minute was used for all tests. Tests were conducted at room temperature, 300<sup>o</sup>, 600<sup>o</sup>, 900<sup>o</sup>, 1200<sup>o</sup>, 1500<sup>o</sup>, and 1800<sup>o</sup> F. (An argon atmosphere was used for elevated-temperature tests up to 1500<sup>o</sup> F to inhibit oxidation of the composites; however, at 1500<sup>o</sup> and 1800<sup>o</sup> F, the specimens were tested in a vacuum capsule.) Tungsten wires given a thermal treatment to simulate infiltration were tested under the tensile test conditions identical to those used to test the composites so that the effects of process thermal treatments on the strength of the fibers and composites could be determined.

Reduction in area of the composites and total elongation after fracture were determined by measurements made with a comparator at a magnification of 50.

Cross-sectional area and volume percent reinforcement data for all composite specimens were obtained by sectioning the failed specimen transversely in an area immediately adjacent to the fracture. The sections were mounted, polished, and photographed at X 50. A wire count was obtained from the photographs, and cross-sectional area and volume percent fiber were calculated, assuming a constant wire diameter.

## Metallographic Studies

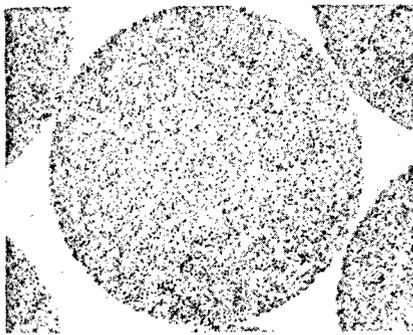
(Metallographic studies were made of the cross sections of the tungsten fiber reinforced copper alloy composites.) All the specimens were swab-etched with Murakami's etchant (10 percent potassium hydroxide, 10 percent potassium ferricyanide, and 100 cc of water) to reveal the structure of the tungsten wires and the reaction zone at the matrix-fiber interface. Photomicrographs were then taken at magnifications of 750 and 250.

(Measurements of the depth of penetration, or reaction of the copper alloy matrix with the tungsten fibers, were made on etched cross sections of the composites at a magnification of 750 with a filar eyepiece. The average depth of penetration was calculated based on the results of measuring a minimum of 10 wires per specimen.

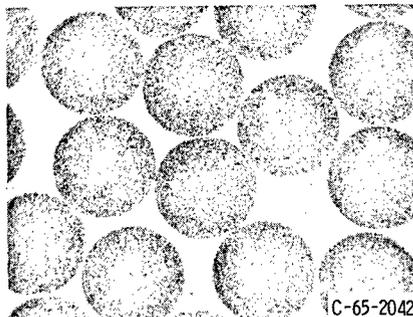
Electron photomicrographs were taken of typical composite cross sections. Parlodion replicas were made from specimens shadowed with chromium at an angle of 30<sup>o</sup>.

## Electron Beam Probe Analysis

(Electron beam probe analyses were made on typical copper alloy matrix composites)



(a) Magnification, 750.



(b) Magnification, 250.

Figure 1. - Pure copper - tungsten fiber reinforced composite. (Reduced 50 percent in printing.)

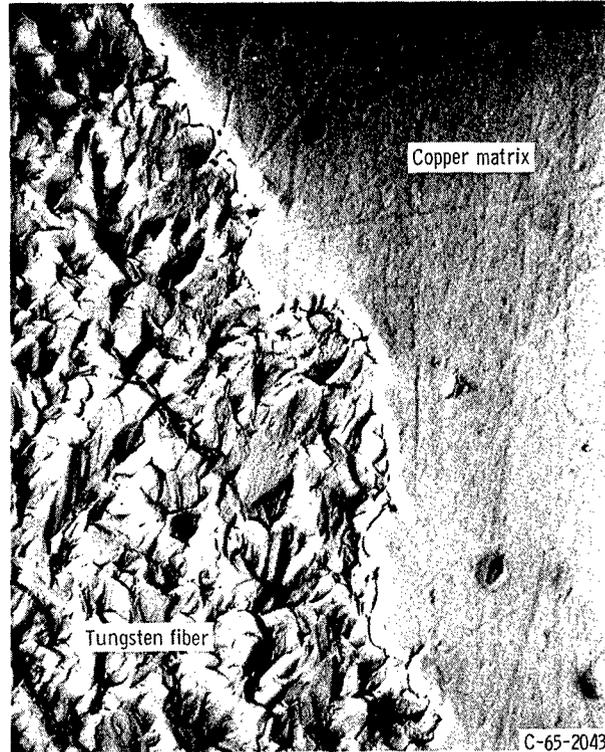


Figure 2. - Electron photomicrograph of copper - tungsten fiber reinforced composite. X20 000. (Reduced 50 percent in printing.)

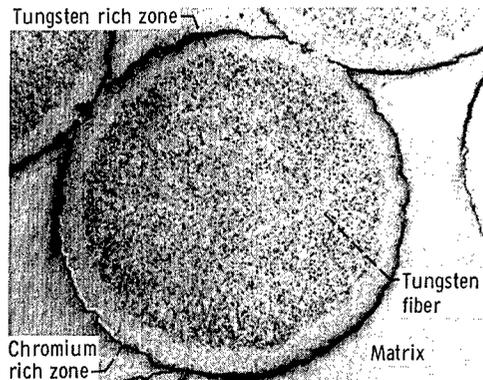
in an attempt to determine concentration gradients in the fiber reaction zones. Concentration determinations were made of the major alloying elements in the composite. The concentration distribution traverses were run completely across a fiber diameter and into the surrounding matrix material. The electron beam probe analyses were conducted by Advanced Metals Research Corporation.

## RESULTS

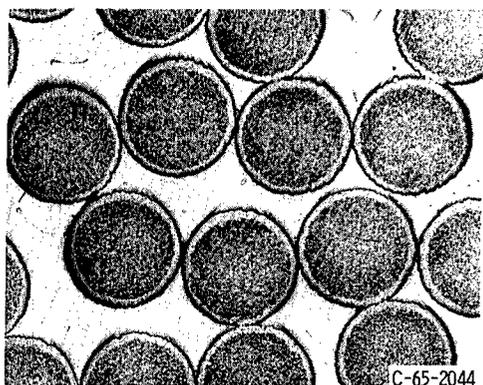
### Microstructural Studies

Copper - tungsten fiber composites. - Microstructures of a cross section of a pure copper - tungsten fiber composite are shown in figures 1 and 2 to furnish a baseline for comparison. Figures 1 and 2 show that alloying with the fiber has not occurred. This is to be expected since tungsten and copper are mutually insoluble.

Copper-2 percent chromium - tungsten fiber composites. - Figures 3 and 4 show a cross-sectional view of a typical copper-2 percent chromium matrix - tungsten fiber composite. Figure 4 shows that two phases are formed at the periphery of the fiber: a single phase tungsten rich structure and a small platelike chromium rich phase. It



(a) Magnification, 750.



(b) Magnification, 250.

Figure 3. - Copper-2 percent chromium - tungsten fiber reinforced composite. (Reduced 50 percent in printing.)

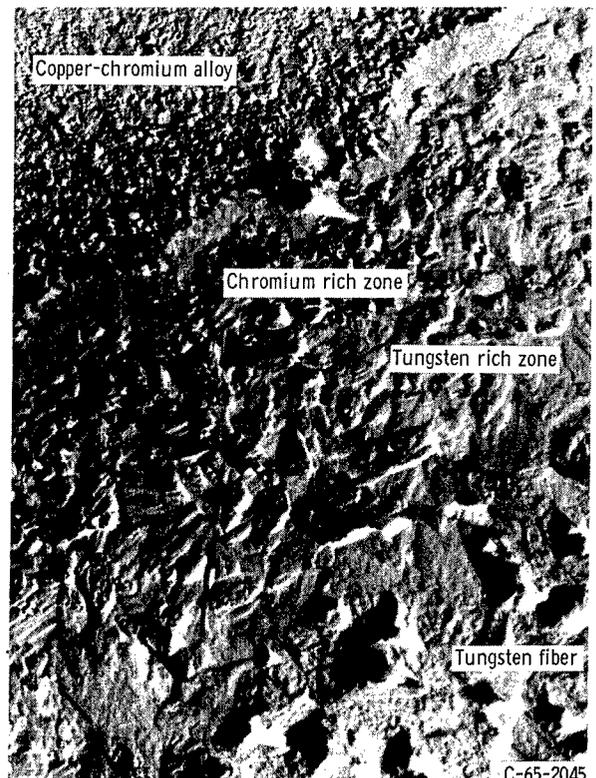


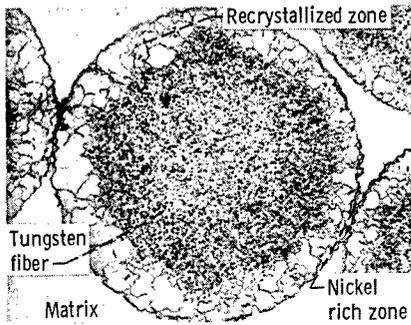
Figure 4. - Electron photomicrograph of copper-2 percent chromium - tungsten fiber reinforced composite. X20 000. (Reduced 50 percent in printing.)

should also be noted that the copper binary matrix is a eutectic type alloy and thus a two-phase structure is formed. The electron photomicrograph (fig. 4) shows the tungsten rich and chromium rich phases.

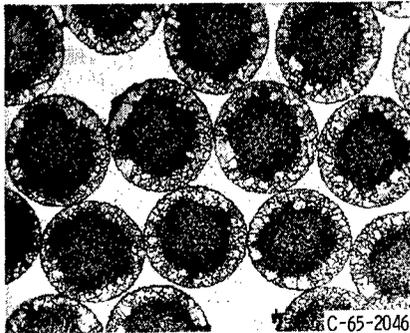
→ Copper-10 percent nickel - tungsten fiber composites. - Recrystallized grains are formed at the periphery of the tungsten fiber/as shown in figure 5. Presumably, this zone contains nickel that has diffused into the tungsten. The recrystallization probably occurred during or subsequent to the diffusion process. (A nickel rich phase formed around the periphery of the tungsten fiber.) The electron photomicrograph shown in figure 6 displays the recrystallized phase at a higher magnification. Other small rounded particles were formed at the periphery of the tungsten fibers. These may have resulted from the dissolving and precipitation of tungsten by the nickel during solidification.

## Electron Beam Probe Analyses

Quantitative values of the concentration distribution of the alloying elements in the



(a) Magnification, 750.



(b) Magnification, 250.

Figure 5. - Copper-10 percent nickel - tungsten fiber reinforced composite. (Reduced 50 percent in printing.)

reaction zones of the fiber in both the copper-nickel and copper-chromium matrix composites could not be obtained. Qualitative results obtained for copper-chromium composites indicated an enrichment of chromium in the matrix adjacent to the matrix-tungsten fiber interface. This phase has a chromium content similar to that of the  $\beta$ -phase in the matrix. Results obtained for the copper-nickel composites indicated that the concentration of nickel in the matrix decreased near the tungsten fiber.

### Reaction Zone Measurements

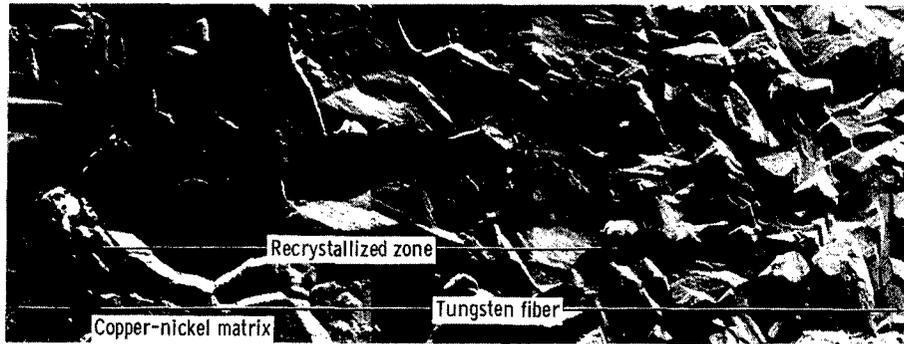
The results of the reaction zone measurements for the copper-2 percent chromium and copper-10 percent nickel matrix systems are given in tables I and II. An increase in fiber diameter was usually noted for the copper-chromium system after infiltration of the matrix material, while no trend was observed in the copper-nickel system. The width of the alloyed fiber zone for the copper-2 percent chromium matrix materials varied from approximately 0.0001 to 0.0006 inch, while that of the copper-10 percent nickel matrix materials varied from 0.0005 to 0.0013 inch. The initial diameter of the tungsten fibers varied by  $\pm 0.00003$  inch from a total diameter of 0.005 inch.

### Tensile Properties

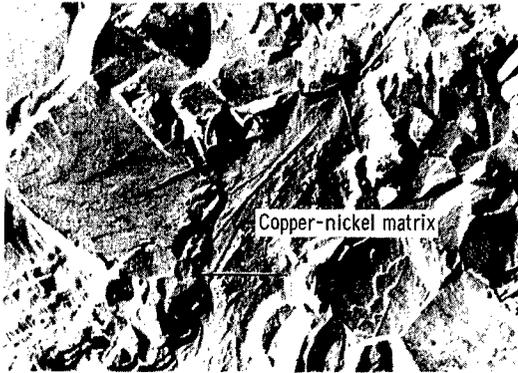
Tungsten fibers. - The elevated-temperature properties of the tungsten fibers used in this study are given in table III and plotted in figure 7. A rapid drop in tensile strength occurs between room temperature and  $900^{\circ}$  F after which a relatively smaller decrease in strength is observed.

The tensile strength of the fibers at room temperature was 335 800 pounds per square inch and decreased to 203 500 pounds per square inch at  $1200^{\circ}$  F. Severe oxidation of the fibers occurred at  $1500^{\circ}$  F even though a protective atmosphere of argon was used during the test; therefore, tensile property data for fibers is presented only for test temperatures up to  $1200^{\circ}$  F.

A plot of percent reduction in area against test temperature is also shown in fig-



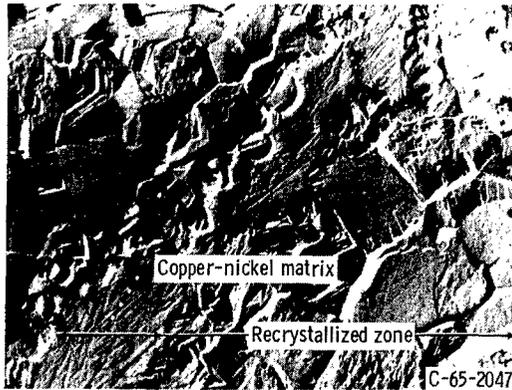
X26 000



X26 000



X26 000



X13 000

Figure 6. - Electron photomicrograph of copper-10 percent nickel - tungsten fiber reinforced composite.

TABLE I. - PENETRATION MEASUREMENTS FOR COPPER-2 PERCENT  
CHROMIUM - TUNGSTEN FIBER REINFORCED COMPOSITE

Test temperature, °F	Specimen number	Total fiber diameter, in.	Unalloyed fiber diameter, in.	Depth of fiber alloy zone, in.	Area alloyed, percent
Room temperature	2	0.00520	0.00417	0.00051	35.7
	3	.00512	.00423	.00044	31.7
	4	.00496	.00444	.00026	19.4
	5	.00507	.00429	.00039	28.2
	6	.00505	.00432	.00037	26.5
	7	.00510	.00471	.00020	14.7
	8	.00503	.00454	.00025	18.6
	300	2	0.00474	0.00371	0.00051
3		.00507	.00462	.00022	17.0
4		.00511	.00469	.00021	15.8
5		.00500	.00460	.00020	15.2
6		.00512	.00473	.00020	14.6
600		2	0.00500	0.00414	0.00043
	3	.00521	.00477	.00022	16.2
	4	.00515	.00476	.00020	13.1
	5	.00517	.00485	.00016	12.0
	6	.00516	.00483	.00017	12.4
	900	2	0.00510	0.00417	0.00046
3		.00519	.00480	.00020	14.5
4		.00512	.00469	.00022	16.1
5		.00514	.00471	.00022	16.0
1200		2	0.00511	0.00434	0.00038
	3	.00513	.00488	.00013	9.5
	4	.00530	.00470	.00030	21.7
	5	.00520	.00490	.00015	11.2
	6	.00500	.00460	.00020	15.4
	7	.00513	.00440	.00037	26.3
	1500	2	0.00507	0.00429	0.00039
3		.00519	.00491	.00014	10.5
4		.00510	.00483	.00013	10.3
5		.00522	.00494	.00014	10.4
6		.00510	.00480	.00015	11.4
7		.00511	.00468	.00022	15.9
8		.00523	.00478	.00023	16.4
1800		1	0.00512	0.00379	0.00059
	2	.00510	.00490	.00010	7.7
	3	.00515	.00491	.00012	9.1
	4	.00507	.00472	.00017	13.4
	5	.00529	.00495	.00017	12.4
	6	.00518	.00483	.00018	13.0

TABLE II. - PENETRATION MEASUREMENTS FOR COPPER-10 PERCENT  
NICKEL - TUNGSTEN FIBER REINFORCED COMPOSITES

Test temperature, °F	Specimen number	Total fiber diameter, in.	Unalloyed fiber diameter, in.	Depth of fiber alloy zone, in.	Area alloyed, percent
Room temperature	1	0.00500	0.00318	0.00091	59.5
	2	.00507	.00324	.00091	59.2
	3	.00511	.00359	.00076	50.6
	4	.00507	.00364	.00071	48.5
	5	.00511	.00388	.00062	42.4
	6	.00507	.00308	.00100	63.1
	7	.00510	.00317	.00096	61.4
300	2	0.00500	0.00306	0.00097	62.4
	3	.00484	.00282	.00101	66.0
	4	.00498	.00290	.00104	66.0
	5	.00481	.00383	.00049	36.6
	6	.00489	.00298	.00095	62.9
	7	.00499	.00291	.00104	66.1
	8	.00496	.00324	.00086	57.3
	9	.00506	.00325	.00090	58.7
	600	2	0.00503	0.00394	0.00087
3		.00477	.00340	.00069	49.2
4		.00500	.00344	.00078	52.7
5		.00480	.00351	.00065	46.5
6		.00485	.00304	.00090	60.7
7		.00495	.00245	.00125	75.5
8		.00498	.00296	.00101	64.7
900		1	0.00504	0.00349	0.00077
	2	.00486	.00320	.00083	56.6
	3	.00480	.00324	.00078	54.6
	4	.00497	.00321	.00088	58.3
	5	.00489	.00352	.00069	48.2
	6	.00494	.00241	.00127	76.2
	7	.00504	.00351	.00077	51.5
1200	2	0.00504	0.00341	0.00081	54.2
	3	.00512	.00387	.00062	42.9
	4	.00505	.00323	.00091	58.9
	5	.00503	.00371	.00066	45.6
	6	.00504	.00345	.00078	53.1
	7	.00502	.00331	.00086	56.5
	8	.00508	.00364	.00072	48.7
	1500	1	0.00506	0.00354	0.00076
2		.00497	.00374	.00062	43.4
3		.00507	.00328	.00089	58.2
4		.00500	.00332	.00084	55.9
5		.00499	.00325	.00087	57.8
6		.00506	.00349	.00079	52.4
1800	1	0.00505	0.00384	0.00060	42.2
	2	.00505	.00364	.00070	48.0
	3	.00511	.00273	.00119	71.3
	4	.00513	.00335	.00089	57.4

TABLE III. - TENSILE PROPERTIES  
OF TUNGSTEN FIBER

Test temperature, °F	Tensile strength, psi (a)	Reduction in area, percent (a)
Room temperature	335 800	28.5
300	271 000	44.4
600	227 800	64.0
900	206 000	72.6
1200	203 500	84.8

<sup>a</sup>Average of at least 5 tests.

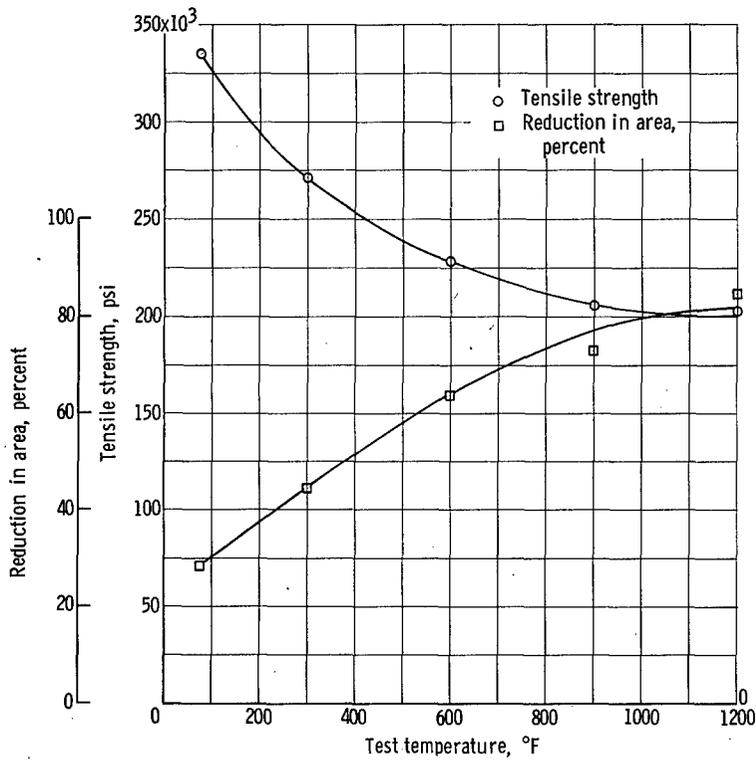


Figure 7. - Tensile strength against test temperature for tungsten fibers.  
Reduction in area against test temperature for tungsten fibers.

TABLE IV. - TENSILE PROPERTIES OF COPPER - TUNGSTEN  
FIBER REINFORCED COMPOSITES

Test temperature, °F	Specimen number	Tensile strength, psi	Fiber volume, percent	Elongation, percent	Reduction in area, percent
Room temperature	1	19 300	0	31.5	99.0
	2	122 000	38.5	19.6	43.6
	3	212 000	60.0	----	41.0
	4	247 500	61.1	6.9	32.0
	5	193 000	61.5	7.9	37.8
	6	221 500	66.0	8.5	33.6
	7	188 000	67.1	8.5	44.7
	8	257 500	68.0	10.9	42.9
	9	218 000	68.9	6.2	36.3
	10	242 000	69.4	9.1	36.4
300	1	13 500	0	53.1	76.6
	2	84 000	27.2	14.9	66.3
	3	171 000	63.8	12.0	55.2
	4	173 800	66.8	9.7	54.1
	5	187 500	70.3	11.6	56.8
600	1	8 200	0	9.4	14.3
	2	57 000	26.0	7.7	40.0
	3	75 000	30.4	12.4	----
	4	144 000	64.8	10.6	47.3
	5	116 500	67.6	9.5	50.5
	6	149 000	69.0	----	48.0
	7	134 500	69.3	9.8	49.6
	8	169 000	74.2	8.6	49.6
900	1	6 300	0	7.9	32.8
	2	11 800	1.8	5.8	3.5
	3	64 500	34.6	1.5	20.1
	4	133 500	64.2	----	22.5
	5	133 000	66.5	6.6	38.0
	6	148 000	68.1	8.4	38.5
	7	135 000	68.2	6.2	35.3
1200	1	4 300	0	47.3	99.0
	2	66 000	28.0	----	11.6
	3	68 000	35.2	6.2	12.0
	4	101 000	43.5	----	20.1
	5	114 000	55.3	7.4	8.7
	6	140 000	64.6	6.0	34.0
	7	142 000	66.8	7.3	20.0
	8	144 000	69.1	----	8.7
1500	1	2 000	0	39.2	----
	2	38 500	17.7	----	3.5
	3	52 000	25.5	12.6	----
	4	56 000	26.6	----	----
	5	95 000	52.0	----	----
	6	90 000	52.1	4.1	5.2
	7	104 000	60.9	----	----
	8	109 500	61.0	7.0	----
	9	125 000	62.2	5.8	10.0
	10	105 000	62.4	----	----
1800	1	24 700	17.9	----	----
	2	56 500	42.1	----	----
	3	73 000	49.0	----	----
	4	90 000	60.4	----	----
	5	88 000	61.6	----	2.0

ure 7. Ductility increased with temperature to 1200° F.

→ Copper-tungsten fiber composites. - Elevated-temperature tensile properties for the copper matrix and copper-tungsten fiber composites are given in table IV. Curves of tensile strength against volume percent fiber for the different test temperatures utilized are shown in figure 8. A linear relation between tensile strength and fiber content was observed for all test temperatures. The intercept of the curve at 100 percent fiber content agrees with the tensile strength values obtained for the tungsten fibers, up to a temperature of 1200° F, the maximum temperature for which the strength of the fibers was obtained.

→ Copper-2 percent chromium - tungsten fiber composites. - The elevated-temperature tensile properties of the copper-2 percent chromium matrix and copper-2 percent chromium - tungsten fiber composites are given in table V. The volume percent fiber content in each specimen was calculated by using the reacted tungsten wire diameter obtained from the penetration measurements, rather than the initial diameter of the fiber.

Figure 9 shows plots of the ultimate tensile strength of the composites against fiber content at the test temperatures investigated. The dashed curve represents the ultimate tensile strength against fiber content relation for pure copper composites. The

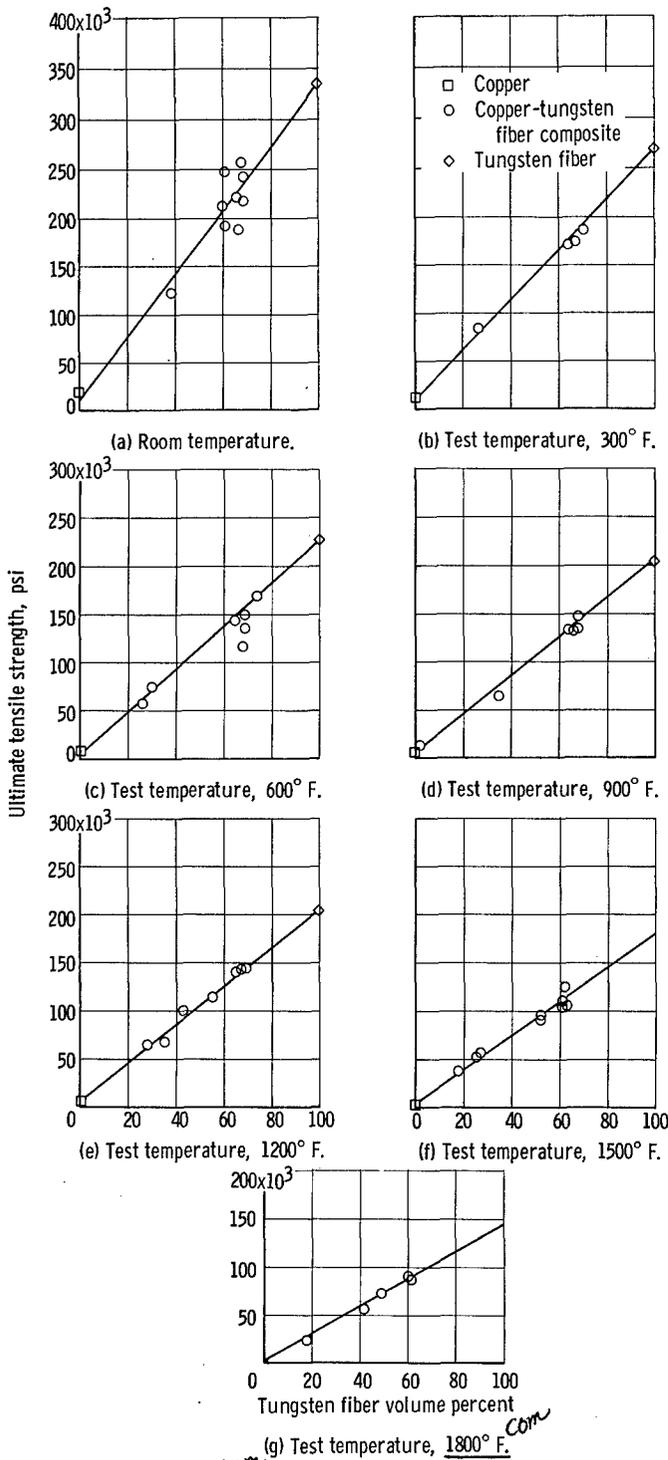


Figure 8. - Tensile strength - fiber content curves for tungsten fiber reinforced copper composites.

TABLE V. - TENSILE PROPERTIES OF COPPER-2 PERCENT  
CHROMIUM - TUNGSTEN FIBER REINFORCED COMPOSITES

Test temperature, °F	Specimen number	Tensile strength, psi	Fiber volume, percent	Elongation, percent	Reduction in area, percent
Room temperature	1	30 500	0	28.6	86.4
	2	30 000	11.9	6.2	23.0
	3	158 000	47.0	----	----
	4	252 500	63.4	13.0	42.6
	5	220 000	68.5	5.2	40.2
	6	217 500	67.9	6.5	41.4
	7	225 000	70.7	7.9	39.9
	8	217 500	71.6	10.6	40.4
300	1	24 500	0	23.3	84.3
	2	51 000	13.4	11.6	48.2
	3	155 500	58.1	11.3	55.9
	4	158 500	61.5	12.5	54.8
	5	177 000	65.9	10.8	53.1
	6	190 000	74.6	13.3	55.2
600	1	19 500	0	25.0	74.9
	2	37 500	12.9	7.7	38.1
	3	129 000	58.2	12.1	57.7
	4	153 000	71.4	10.5	52.0
	5	147 000	72.5	8.3	55.5
	6	161 500	76.9	8.7	52.6
900	1	12 300	0	12.1	30.7
	2	81 500	39.0	5.0	34.0
	3	121 500	61.6	6.8	45.0
	4	144 000	70.0	7.3	37.7
	5	145 500	72.5	6.9	43.3
1200	1	7 700	0	14.9	27.1
	2	60 000	31.2	4.2	24.0
	3	85 000	37.4	----	30.8
	4	95 500	50.2	7.5	12.0
	5	115 000	54.6	----	35.2
	6	126 500	65.4	8.4	34.0
	7	130 000	70.9	7.3	24.0
1500	1	3 500	0	23.6	76.1
	2	31 000	16.4	2.9	3.5
	3	73 000	35.7	----	----
	4	76 500	43.4	3.7	----
	5	93 500	45.9	----	12.0
	6	137 000	71.1	----	----
	7	136 000	71.7	2.2	13.7
	8	135 000	73.5	----	16.9
1800	1	43 500	29.3	----	10.3
	2	62 000	37.3	----	15.3
	3	87 500	50.7	----	----
	4	80 300	53.8	----	7.0
	5	88 000	63.1	----	----
	6	92 000	73.5	----	----

reacted tungsten fibers were leached out of the copper-chromium matrix by using concentrated hydrochloric acid and tested at temperatures up to 1200° F. The tensile strength of the fibers was lowered at a test temperature of 1200° F by surface oxidation. Tensile data for these fibers is thus only given up to 900° F as shown in table VI.

Average tensile strengths of the alloyed fibers are represented by the data points at 100 percent fiber content in figure 9. A linear relation exists between ultimate tensile strength and fiber content for the copper-chromium - tungsten-fiber reinforced composite system. At high fiber contents the difference in ultimate tensile strength for the alloyed composite is only slightly lower than that for the copper composites in which alloying with the fiber did not occur, while at low fiber contents the alloyed composites are slightly stronger.

Copper-10 percent nickel - tungsten fiber composites. Elevated-temperature tensile properties of the copper-10 percent nickel matrix and copper-10 percent nickel - tungsten fiber composites are given in table VII. Curves of tensile strength against fiber content for each temperature investigated are shown in figure 10. The volume percent fiber content was based on the reacted fiber diameter. All the data points for the copper-nickel - tungsten fiber composites fall below the dashed curve representing the tensile strength

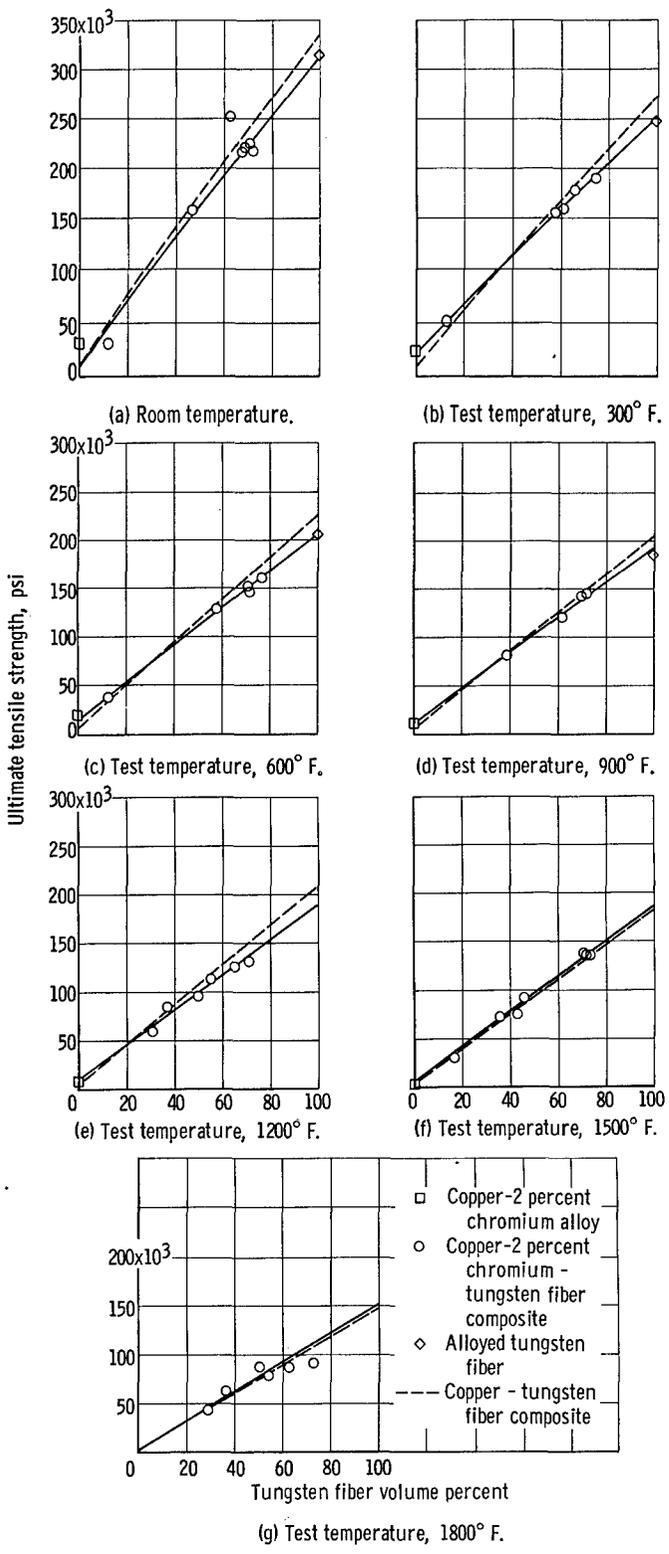


Figure 9. - Tensile strength - fiber content curves for tungsten fiber reinforced copper-2 percent chromium composites.

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TABLE VI. - TENSILE PROPERTIES OF  
LEACHED-OUT TUNGSTEN FIBERS  
ALLOYED WITH CHROMIUM

Test temperature, °F	Reduction in area, percent (a)	Tensile strength, psi (a, b)
Room temperature	30.9	316 000
300	50.7	247 000
600	71.9	207 000
900	77.2	187 000

<sup>a</sup>Average of at least 5 tests.

<sup>b</sup>Based on alloyed wire diameter.

against volume percent fiber relation for copper - tungsten fiber composites. An increase in tensile strength above that of room temperature is noted in the plot representing the data obtained at 300° F. From test temperatures at 300° up to 1800° F the decrease in tensile strength is gradual. A linear relation appears to exist between tensile strength and fiber content at test temperatures of 300° F and above. The reacted tungsten fibers were leached out of the copper-nickel matrix using concentrated hydrochloric acid. The fibers were extremely brittle. Attempts to determine the tensile strength of the fibers proved unsuccessful because of the brittleness of the material and gripping problems.

## PERCENT ELONGATION AND REDUCTION IN AREA

The average percent elongation against test temperature for the three different composite systems containing 70 volume percent fiber is shown in figure 11. Below 600° F the copper-nickel - tungsten fiber composites were not as ductile as either the copper-chromium - or pure copper - tungsten fiber composites. At room temperature the copper-nickel - tungsten fiber composites failed by brittle fracture.

The average percent reduction in area as a function of test temperature for the three different composite systems containing 70 volume percent fiber is shown in figure 12. Maximum ductility occurs at approximately 300° F for both the copper-chromium - and copper - tungsten fiber composites. The ductility of the copper-nickel - tungsten fiber composites is much less than that obtained for the other systems at all the temperatures investigated.

## DISCUSSION

### Composite Tensile Properties

The tensile strength of unalloyed fiber composites was generally higher than alloyed fiber composites. The difference in strength between alloyed fiber composites and unalloyed fiber composites, however, was less at elevated temperatures than at room

TABLE VII. - TENSILE STRENGTH AND PROPERTIES OF  
 COPPER-10 PERCENT NICKEL - TUNGSTEN  
 FIBER REINFORCED COMPOSITES

Test temperature, °F	Specimen number	Tensile strength, psi	Fiber volume, percent	Elongation, percent	Reduction in area, percent
Room temperature	1	35 300	66.0	----	----
	2	27 000	69.0	----	----
	3	110 000	70.5	----	----
	4	106 000	70.8	----	----
	5	71 000	71.2	----	----
	6	68 500	72.3	----	----
	7	94 000	73.5	----	----
300	1	12 400	0	9.8	8.8
	2	89 000	48.6	----	----
	3	98 000	49.4	2.9	8.8
	4	109 000	63.1	3.2	4.4
	5	118 600	64.8	8.9	13.7
	6	138 000	66.0	6.6	7.0
	7	108 000	66.8	5.9	5.8
	8	134 000	67.3	2.0	3.5
	9	137 000	69.0	3.5	2.5
600	1	6 200	0	7.8	8.8
	2	53 000	35.5	----	5.2
	3	92 000	58.7	10.3	13.7
	4	86 500	61.3	3.5	5.9
	5	100 000	62.8	10.3	13.7
	6	93 000	63.4	10.4	13.7
	7	80 000	67.7	----	14.2
	8	96 000	70.5	----	----
900	1	6 400	0	10.1	8.8
	2	37 500	25.9	0.8	5.2
	3	76 000	58.0	----	12.3
	4	90 500	62.6	10.1	12.8
	5	81 500	64.6	----	5.1
	6	87 000	66.2	7.2	11.7
	7	88 400	70.1	1.2	7.6
	8	99 000	71.8	5.8	20.1
1200	1	4 700	0	5.4	3.5
	2	36 500	27.5	----	----
	3	78 000	52.6	----	----
	4	90 000	68.6	2.2	13.7
	5	83 000	69.0	5.0	15.5
	6	80 000	69.5	5.6	16.9
	7	81 000	72.3	7.4	13.5
	8	102 000	74.1	----	----
1500	1	53 500	44.8	----	----
	2	74 000	59.4	4.1	14.3
	3	81 000	68.3	----	10.3
	4	71 500	68.8	6.0	15.5
	5	66 500	69.1	1.9	3.5
	6	65 000	69.3	3.6	2.5
1800	1	58 000	50.6	----	16.9
	2	60 000	53.0	----	----
	3	54 500	65.3	----	----
	4	70 500	73.0	----	3.5

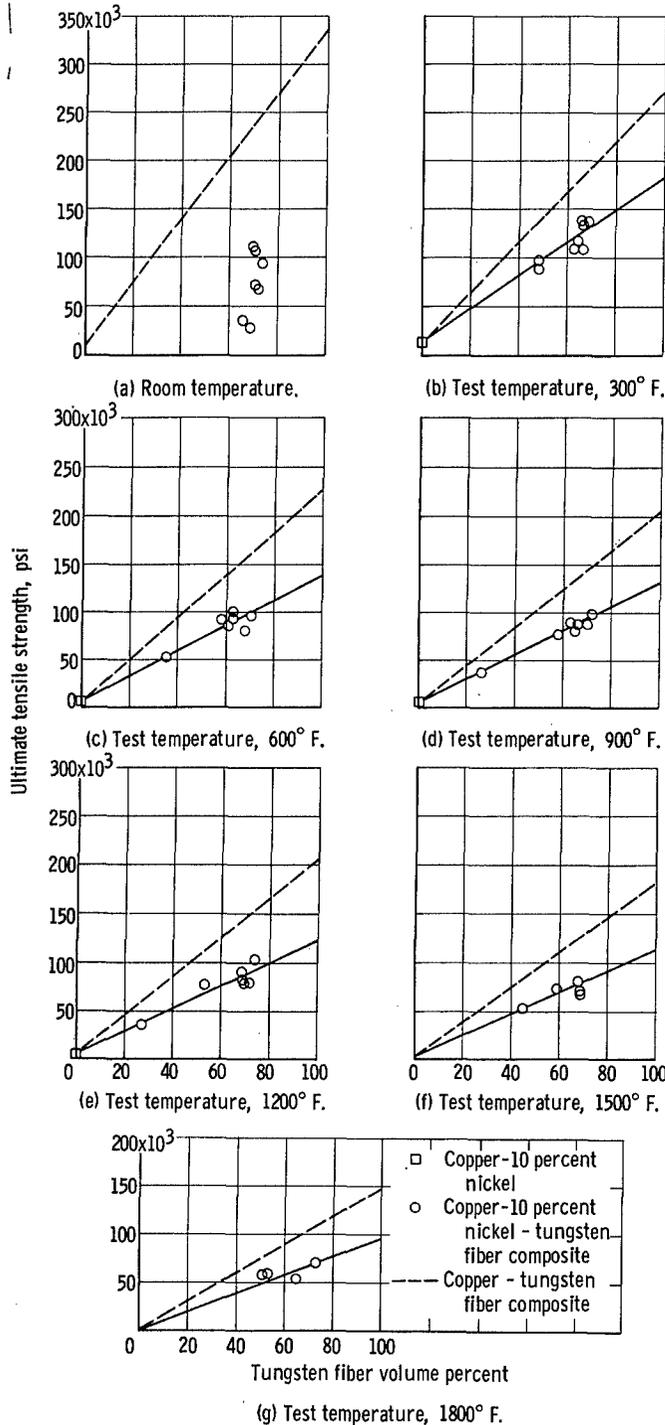


Figure 10. - Tensile strength - fiber content curves for tungsten fiber reinforced copper-10 percent nickel composites.

temperature. A cross plot of the tensile strength against test temperature for all three matrix systems having a fiber content of 70 volume percent is shown in figure 13(a). At room temperature the copper - tungsten fiber composites have a tensile strength of 235 000 pounds per square inch, and the copper-chromium - and copper-nickel - tungsten fiber composites have tensile strengths of 220 000 and 70 000 pounds per square inch, respectively. At 1800° F the copper - tungsten fiber and copper-chromium - tungsten fiber composites have equivalent tensile strengths, 100 000 pounds per square inch, while the copper-nickel - tungsten fiber composites have a tensile strength of 65 000 pounds per square inch, which is almost equal to its average room-temperature tensile strength.

A plot of the unreinforced tensile strength of the matrix against test temperature is shown in figure 13(b). The copper and copper-nickel matrix materials that were not reinforced by tungsten fibers have equivalent tensile strengths with increasing test temperature. The copper-chromium matrix, however, is slightly stronger than the other two matrix materials.

The effect of alloying on the tensile properties of these composites can be determined by comparing the tensile properties of alloyed tungsten fiber composites with those of the mutually insoluble copper - tungsten fiber composites. Any change in ten-

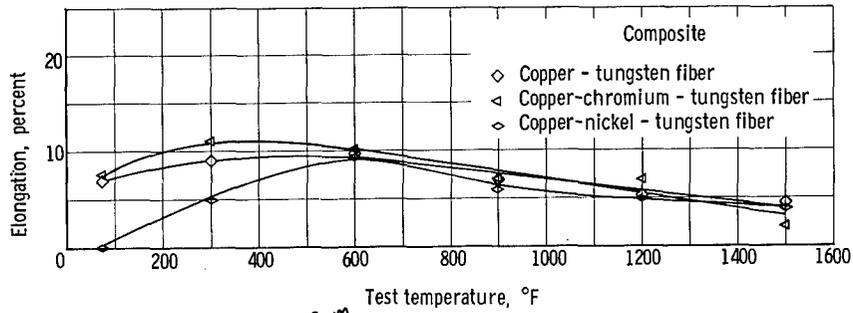


Figure 11. - Average percent <sup>Com</sup> elongation against test temperature for copper- and copper alloy-tungsten fiber reinforced composites. Tungsten fiber, 70 volume percent.

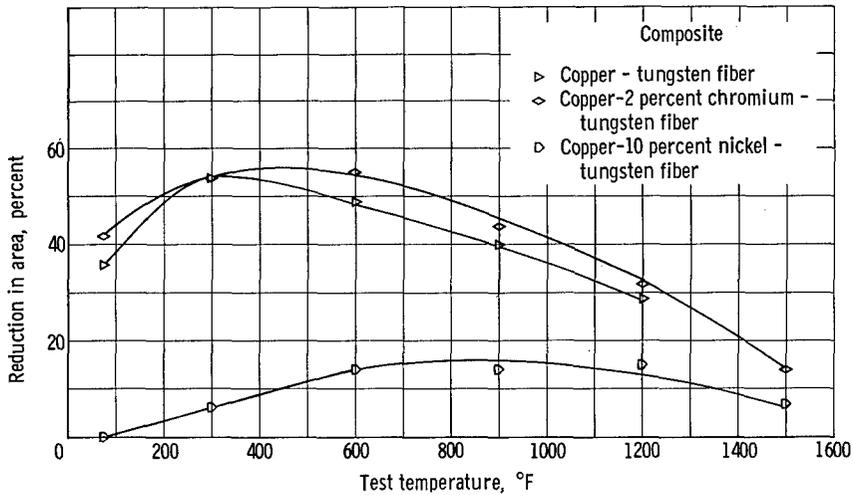


Figure 12. - Average percent <sup>Com</sup> reduction in area against test temperature for copper- and copper alloy-tungsten fiber reinforced composites. Tungsten fiber, 70 volume percent.

sile strength of the copper alloy composite relative to the copper composite must be due to the alloying element addition made to the copper. In order to more fully understand these effects, however, it is necessary to determine the contribution of each component in the composite.

On the basis of previous work (ref. 1) the ultimate tensile strength of continuous fiber reinforced composites can be represented by the following equation:

$$\sigma_c = \sigma_f A_f + \sigma_m^* A_m \quad (1)$$

where

- $\sigma_c$  ultimate tensile strength of composite (assuming cross-sectional area equal to 1)
- $A_f$  area fraction occupied by fiber
- $\sigma_f$  ultimate tensile strength of fiber

$A_m$  area fraction occupied by matrix

$\sigma_m^*$  stress on matrix at strain where ultimate tensile strength of fiber is achieved

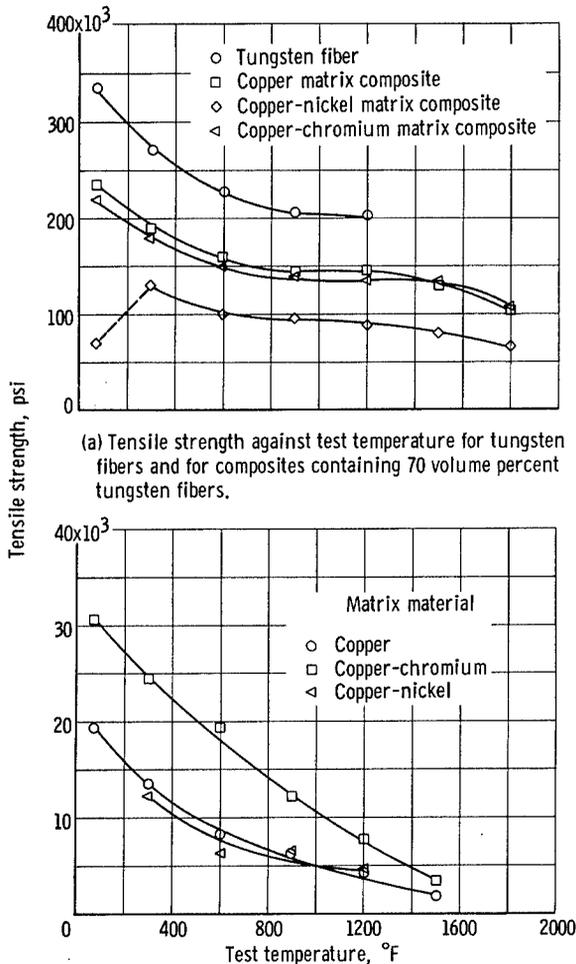
Equation (1) predicts a linear relation between ultimate tensile strength and fiber content. The results of this investigation show that a linear relation between tensile strength and fiber content applies for copper - tungsten fiber reinforced composites at all the test temperatures investigated in this study. In addition, the tensile strength values obtained for fibers tested at temperatures up to 1200° F agree with those predicted by equation (1) using copper - fiber reinforced composite tensile strength results. This agreement is also expected at 1500° and 1800° F, but oxidation of the fibers prevented an independent determination of properties. Values for  $\sigma_m^*$  were not determined independently. Values for  $\sigma_m^*$  calculated from composite data are, however, lower

than those obtained for the ultimate tensile strength of the matrix. This would imply that the tensile strength results obtained for the composites are in agreement with equation (1).

Equation (1) neglects any interaction between the fiber and matrix and has been previously limited to mutually insoluble components. The results of this investigation show that a linear relation between tensile strength and fiber content also applies to tungsten fiber reinforced composites with the two different types of alloyed matrices studied in this investigation. Assuming that any reaction zones formed between the fiber and the matrix contribute linearly in proportion to their area fraction to the ultimate strength of a composite yields the following relation for the ultimate tensile strength:

$$\sigma_c = \sigma_m^* A_m + \sum_{i=1}^{i=n} \sigma_{r,i}^* A_{r,i} + \sigma_f A_f \quad (2)$$

where  $\sigma_{r,i}^*$  is the average stress on a given reaction zone at the strain where the unalloyed portion of the fiber reaches its ultimate



(a) Tensile strength against test temperature for tungsten fibers and for composites containing 70 volume percent tungsten fibers.

(b) Tensile strength against test temperature for unreinforced matrix materials.

Figure 13. - Tensile strength against test temperature for composites containing 70 volume percent tungsten fiber and for individual constituents.

mate strength and  $A_{r,i}$  is the area fraction of reaction zone. It is assumed in equation (2) that the reaction zones are ductile enough to strain at or beyond the ultimate tensile strength of the fiber and that the tensile strength of the unalloyed portion of the fiber is unaffected by the presence of the alloyed zone.

The preceding is analogous to the simple case of an unreacted fiber composite, if the reacted fiber can be treated as a simple composite:

$$\sigma_c = \sigma_m^* A_m + \sigma_f' A_f' \quad (2a)$$

where  $\sigma_f' A_f'$  is the tensile strength contribution of the total fiber

$$\sigma_f' A_f' = \sigma_r A_r + \sigma_f A_f \quad (2b)$$

And

$$\sigma_c = \sigma_m^* A_m + \sigma_r A_r + \sigma_f A_f \quad (3)$$

which is equation (2) when  $n$  is equal to 1, the case for one zone of reacted material. Two reacted zones were obtained in the current investigation. One, however, was present in such a small quantity that it can be neglected. Equation (3) describes the copper-chromium - tungsten fiber composite behavior.

A plot of composite tensile strength against percent fiber content should be linear with the zero fiber intercept being  $\sigma_m^*$  (stress on the matrix at the strain where the fiber reaches its ultimate tensile strength) and the 100 percent fiber intercept being the ultimate strength of the reacted fiber  $\sigma_f'$ . This, of course, assumes similar reacted fibers within a given composite. It may be recalled that the data shown in figure 9 represents such a plot for the copper-chromium - tungsten fiber composites. The linearity of the composite data tends to substantiate the validity of the assumptions required for equation (2). The validity would be further indicated if the intercept at 100 percent fiber content agreed with the ultimate tensile strength values for similarly reacted fibers obtained independently. Such a data comparison was made for the copper-chromium - tungsten fiber composites at 600° F. The 600° F curve in figure 9 represents a least squares fit through the composite data. The extrapolation of this curve to 100 percent fiber content gave a value of 205 500 pounds per square inch for the fiber ultimate tensile strength. The composite data points were for specimens containing fibers with an average reaction zone equal to 17 percent of the total fiber area. Fibers leached out from the copper-chromium - tungsten fiber composites were tensile tested at the same test temperature so that an ultimate tensile strength value was independently obtained for similarly reacted fibers. The ultimate tensile strength data were plotted (fig. 14)

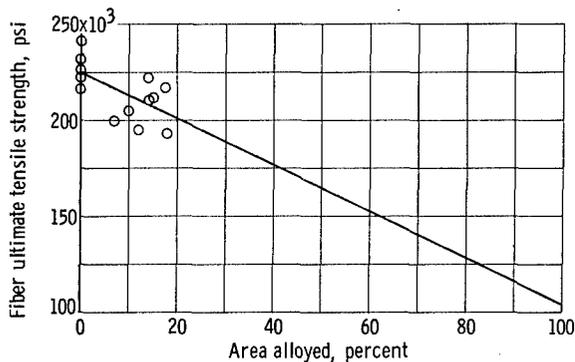


Figure 14. - Fiber tensile strength against percent of fiber alloyed with chromium. Test temperature, 600° F.

against the area of the fiber reacted. The reacted areas were obtained from posttest metallographic examination. The data for leached fibers show scatter about equivalent to that for unreacted fibers. The least squares fit through the data indicated that an ultimate tensile strength value of 204 000 pounds per square inch results for a fiber which has a reaction zone that is 17 percent of the total area of the fiber. This value agrees very well with the ultimate tensile strength of 205 500 pounds per square inch obtained from extrapolation of composite data. This agreement tends to verify that equation (2a) describes the behavior of reacted composites in a manner similar to that shown in reference 1 for mutually insoluble composites.

There are some additional verifications that would be helpful. Among these is a more accurate determination of  $\sigma_m^*$ . The value obtained from extrapolation of the 600° F data of figure 9 is 13 700 pounds per square inch, which is in general agreement with the value that would be predicted: specifically it is slightly less than the ultimate tensile strength (19 500 psi). Since data for leached fibers with a greater range of reacted area and for the entire temperature range studied were not obtained, an indication of the tensile strength of reacted fibers for other temperatures may be gained by replotting the data for reacted fibers obtained from composite specimen tensile tests. Also, an indication of a linear change of fiber properties with a linear increase of reacted area would tend to support the validity of equation (2b). The tensile strength of reacted fibers was calculated from composite data by using equation (2a). The following values were used:  $\sigma_m^*$  was obtained from figure 9 and  $\sigma_c$ ,  $A_m$ ,  $A_{f,r}$  were measured. The cross plot of the ultimate tensile strength of the reacted fibers against the percent of the fiber that was alloyed is shown for copper-chromium - tungsten fiber composites tested at 1200° F in figure 15(a). There appears to be a linear decrease in fiber strength with an increased area of reacted fiber, which tends to confirm that equation (2b) applies. This is further implied by the agreement of values for the unalloyed fiber obtained by testing individual fibers and from the zero alloyed fiber intercept of figure 15(a). Similar results were shown for copper-nickel - tungsten fiber composites (figs. 15(b) and (c)) tested at 600° and 1500° F, which implies that a similar relation exists for the copper-nickel - tungsten fiber composites, at least for the range of variables tested.

Equation (2a) has been verified, and equation (2b) appears to be valid. Equation (3) thus can be assumed to describe the tensile strength behavior of the alloyed composite systems studied in this investigation. It must be cautioned, however, that equations (2) and (3) do not apply in all instances where alloying reactions occur in composite systems.

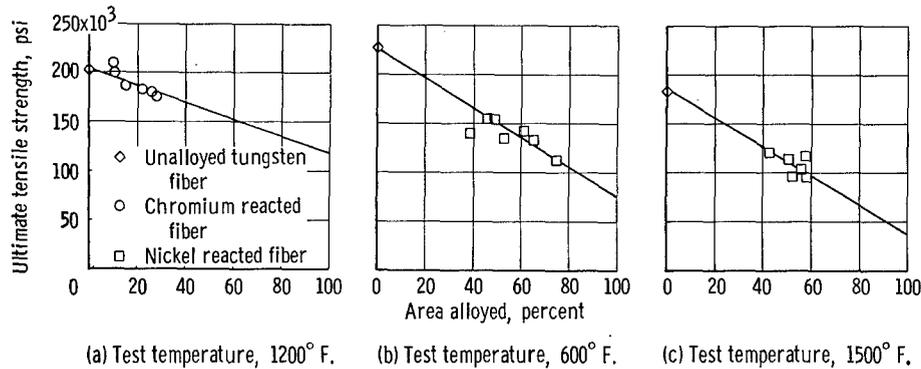


Figure 15. - Fiber tensile strength against percent of fiber alloyed.

For example, it was shown in reference 2 that the brittle behavior of an alloy zone coupled with the notch sensitivity of the reinforcing fiber reduced the properties of the fiber. This reduction in properties would not be predicted by equation (2) since it was assumed that the tensile strength of the unalloyed portion of the fiber is unaffected by the presence of the alloy zone. Likewise, an increase in composite tensile strength could occur in some instances relative to that predicted by equation (2).

Although alloying reactions influenced the tensile properties of the copper-chromium - tungsten fiber composites, the net effect was slight relative to copper composites in which alloying reactions did not occur (fig. 9). Figures 14 and 15(a) show that the decrease in strength for the chromium reacted fibers is relatively slight since only a small portion of the fiber reacted with the chromium and since the alloy zone itself appears to be quite strong. Because at high volume fiber contents the fibers are the major load carriers of the composite, the tensile strength of copper-chromium - tungsten fiber composites at high fiber contents should be slightly less than that of copper-tungsten fiber composites having equivalent fiber contents. At low fiber contents, however, a greater share of the load is carried by the matrix material. The contribution of the copper-chromium alloy matrix to the tensile strength of the composite (fig. 13) is greater than that of the (unalloyed) oxygen-free high-conductivity copper matrix (at temperatures up to 1500° F). Consequently, at some low volume percent fiber content and at temperatures below 1500° F, the decrease in composite strength due to reaction of the fiber may equal the increase in composite strength due to alloying the copper. The tensile strength of the copper-chromium - tungsten fiber composite is lower than that for the pure copper composites at high volume percent fiber contents, but the copper-chromium - tungsten composite is slightly stronger than the pure copper composites, as shown in figure 9 at low volume percent fiber contents. The fiber content where this occurs can be approximated by use of equations (1) and (2) and the conditions where the  $\sigma_{Cu \text{ alloy}} = \sigma_c$ , and  $A_{f,1} = A_{f,2}$ .

At 900° F, for example, a fiber content of 31 percent is obtained. Thus, at this temperature and below this volume percent fiber content, the copper chromium alloy

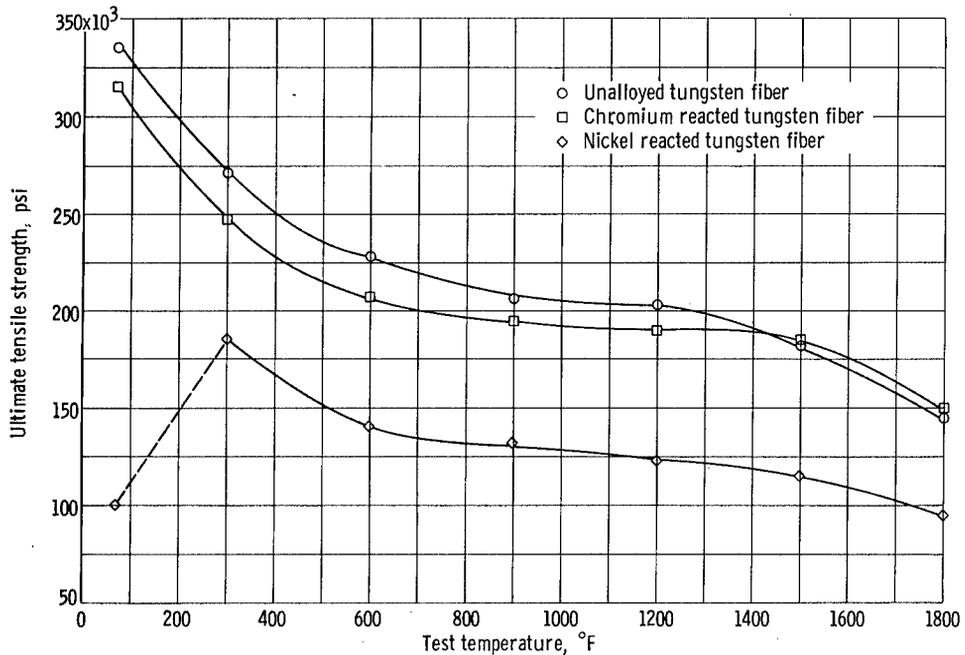
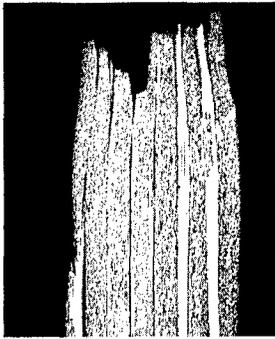


Figure 16. - Fiber tensile strength against test temperature.

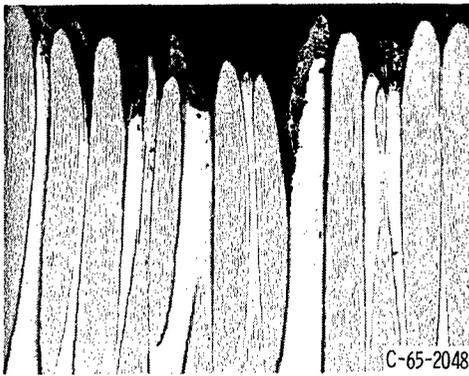
composite is stronger than the pure copper composite.

As has been previously shown with the copper-chromium matrix system, the fiber tensile strength could be determined from composite data and equation (2). This is also assumed for the copper-nickel matrix system for which independent data for the fibers could not be successfully obtained. A plot of the fiber tensile strength, calculated from composite data, against area percent reaction zone for the copper-nickel composites is shown in figures 15(b) and (c). As the depth of the reaction zone increases, the tensile strength of the reacted fiber is seen to decrease. A linear relation appears to exist between the tensile strength of the reacted fiber and the percent reaction zone present. Extrapolation of the curve to 100 percent reacted zone gives an approximate value for the tensile strength contribution of the reacted and recrystallized zone. It can be seen from figure 15 that the tensile strength contribution of the chromium reacted zone is much higher than that contributed by the nickel reaction zone. Even at a temperature of 1200° F the tensile strength of the chromium reaction zone is greater than the 600° F tensile strength of the nickel reaction zone. Not only is the nickel reaction zone weaker than the chromium reaction zone, but it also forms a larger reaction zone with the fiber. This larger reaction zone accounts for the much lower tensile strength values for the copper-nickel matrix composites as compared to the copper-chromium matrix composites.

The tensile strength of the reacted tungsten fibers is compared with that of the unalloyed fibers in figure 16. Chromium reacted fibers are slightly weaker than pure tung-



(a) Copper-2 percent chromium matrix. Room temperature. X50.



(b) Copper matrix. Test temperature, 1200° F. X100.  
Figure 17. - Fracture edges of tungsten fiber reinforced composite. (Reduced 50 percent in printing.)

sten fibers up to 1500° F, after which they appear to be slightly stronger than or equal to the unalloyed fibers. The nickel reacted fibers are significantly weaker than the unreacted fibers. The increase in strength observed between room temperature and 300° F for the nickel reacted fibers is believed to be due to the increased ductility of the reacted zone and the improved notch properties of the fiber. At room temperature the copper-nickel matrix composites fail in a brittle manner as evidenced by elongation and reduction in area measurements. Load against displacement, or motion of the cross head of the Instron curves, show that the composites failed elastically. This failure suggests that a notch embrittlement effect has occurred. The nickel reacted tungsten wire is extremely brittle at room temperature. Presumably, the nickel alloy zone fails early in the test at room temperature and introduces a circumferential notch in the fiber that leads to notch embrittlement. This effect was reported in a previous investigation (ref. 2).

The transition temperature from a ductile to a brittle type fracture for the copper-nickel - tungsten fiber composites was observed to be approximately 300° F. At 300° F and above the recrystallized fiber zone is believed to be ductile enough to allow the nonrecrystallized portion of the fiber to reach its ultimate tensile strength. The nonrecrystallized fiber itself is less notch sensitive at the higher test temperatures.

The copper-nickel - tungsten fiber system does not exhibit the tensile strength crossover that occurred in comparing the copper - with the copper-chromium - tungsten fiber system because the copper-nickel alloy is not noticeably stronger than the unalloyed copper. Thus, at all volume percent fiber contents, the nickel system is weaker in tension than the copper composites.

### Reduction in Area and Elongation

The reduction in area values obtained for the composites gives an indication of the shear bond strength at the fiber-matrix interface. If the bond between the fiber and the

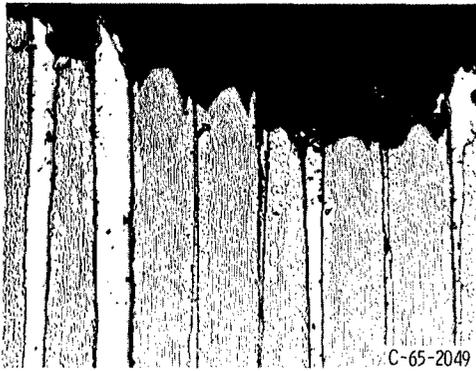


Figure 18. - Fracture edge of copper-10 percent nickel - tungsten fiber reinforced composite. Test temperature, 1200° F. X150. (Reduced 50 percent in printing.)

matrix is strong, necking of the composite occurs and the fiber alignment follows the contour of the necked region of the composite (fig. 17(a)). If a weak bond exists, however, the matrix-fiber bond is broken during the test (fig. 17(b)) and necking of the composite is slight. The apparent ductility of the composite is thus not necessarily indicative of the ductility of the individual constituents. For example, a 30 percent reduction of area was measured at 1200° F for copper matrix composites containing 70 volume percent fibers, while that of the fiber and matrix is 85 and 99 percent, respectively. At this temperature the bond between the

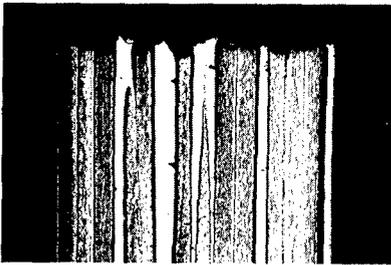
matrix and the fiber is weak and shearing occurs at the interface. On the other hand at temperatures below approximately 600° F the fiber alignment follows the contour of the necked region of the copper composites, and only a slight amount of shearing occurs at the interface. The ductility data of the composites agree with those expected since they are between the ductility of the individual constituents.

Copper - and copper-chromium - tungsten fiber composites exhibit similar reduction in area values with increasing test temperatures. Copper-nickel - tungsten composites, however, show lower reduction in area values than those of the other two systems. The lower values are due to the recrystallized zone formed around the fiber. It is evident from figure 18 that the recrystallized zone is less ductile than the unalloyed fiber zone and that the bond between the fiber and the recrystallized region is broken. The unreacted portion of the fiber, however, is very ductile and necks to failure. The ductility behavior of the recrystallized zone and the bond strength between this zone and the unreacted portion of the fiber thus control the measured ductility of the composite.

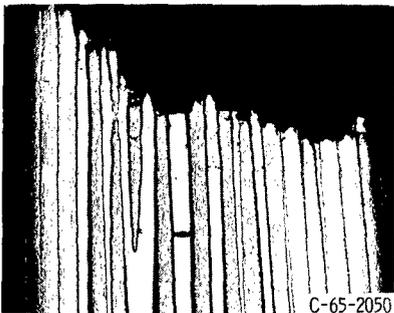
Figure 19 shows that at room temperature the unalloyed portion of the fiber fails in a brittle manner, while at 300° F it fails in a ductile manner, as evidenced by fiber necking. Thus, the transition temperature from a brittle to a ductile type fracture was approximately 300° F. The marked increase in tensile strength at about this temperature further substantiates the transition temperature.

Elongation data for the copper - copper-chromium - and copper-nickel - tungsten fiber composite specimens did not show variations similar to those described for the reduction in area data. At test temperatures above 300° F elongation data for composites with similar fiber contents were essentially the same.

## Microstructural Studies



(a) Room temperature. X50.



(b) Test temperature, 300° F. X50.

Figure 19. - Fracture edge of copper-10 percent nickel - tungsten fiber reinforced composite.

In the cross-sectional view of the copper-chromium - tungsten fiber composite, shown in figure 3, p. 6, four zones are apparent: namely, an  $\alpha + \beta$  copper alloy zone, a chromium rich zone, an alloyed tungsten rich zone, and an unalloyed portion of the tungsten fiber. The chromium rich zone present at the periphery of the fiber is believed to be the  $\beta$ -phase of the copper eutectic type matrix into which some tungsten may have diffused. The four zones apparent in figure 3 may be formed in the following manner. At the infiltration temperature, 2200° F, the copper-chromium alloy is completely liquid. The chromium in this state diffuses much faster into the tungsten fiber than the tungsten which goes into solution, resulting in an increase in fiber diameter. As the liquid cools,  $\beta$  crystals (rich in Cr) precipitate out of the supersaturated solution and form a layer around the tungsten fiber. This layer formation would be expected since the energy to nucleate on the

fiber surface is less than that required to nucleate in the copper. The same explanation can be used for the increased concentration of chromium at the fiber matrix interface previously observed in the electron beam microprobe studies. The concentration of chromium at the fiber surface is thus larger than that in the fiber, and diffusion of the chromium into the tungsten takes place. With additional cooling general precipitation results and  $\beta$  also forms in the matrix to yield an  $\alpha + \beta$  eutectic structure.

Diffusion data for nickel - tungsten indicate that the volume diffusion of tungsten into nickel is relatively rapid (refs. 12 and 13) compared to nickel volume diffusion into tungsten which is most likely small. While surface diffusion coefficients for tungsten in nickel and nickel in tungsten have not been reported in the literature, Vacek (ref. 14) has reported some diffusion results which are pertinent. Interpenetration of both elements was observed, by pressing a nickel compact against a tungsten compact at 1300° C, to be appreciable, but the nickel content on the tungsten-rich side was higher than the tungsten content on the nickel-rich side at the same distance from the interface and after the same time interval. Since the compacts at the start were both porous, the nickel content on the tungsten side is probably an indication of surface diffusion rather than relative volume diffusion. Activated sintering of tungsten by nickel has been reported by several

investigators (refs. 14 and 15) and presumably results from increased surface energy driving forces.

A nickel-rich phase at the periphery of the fiber is evident in figure 5 (p. 7). Since both copper and nickel are completely soluble in each other, the nickel-rich phase is believed to be a single-phase solid solution of tungsten in nickel.

A penetration depth of 0.0002 inch should result based on bulk diffusion coefficient calculations (ref. 13). Penetration measurements show a depth of 0.0005 to 0.0013 inch. The enhanced penetration suggests that grain boundary diffusion of nickel into tungsten appears likely.

## SUMMARY OF RESULTS

An investigation was conducted to study the effects of selected alloying elements on the elevated-temperature tensile properties of tungsten-fiber-reinforced composites. The following results were obtained:

1. The tensile strength of unalloyed fiber composites was generally higher than that of alloyed fiber composites. The difference in strength between alloyed fiber composites and unalloyed fiber composites, however, was less at elevated temperatures than at room temperature. In addition, the low fiber content copper-chromium - tungsten fiber composites were stronger than the pure copper - tungsten fiber composites having equal fiber contents. The chromium alloyed fibers were slightly lower in strength than the unalloyed fibers; however, the alloyed matrix was stronger than the unalloyed matrix. Thus, for low fiber content composites, the increased strength contribution of the matrix may result in a net increase in strength despite the lower fiber strength.

2. The ultimate tensile strength of all the composite systems studied at elevated temperatures was proportional to the properties of the components and their respective area as shown by the equation

$$\sigma_c = \sigma_m^* A_m + \sum_{i=0}^{i=n} \sigma_{r,i}^* A_{r,i} + \sigma_f A_f$$

where

$\sigma_c$  ultimate tensile strength of composite (assuming cross-sectional area equal to 1)

$\sigma_m^*$  stress on matrix at strain where ultimate tensile strength of fiber is achieved

$A_m$	area fraction occupied by matrix
$\sigma_{r,i}^*$	average stress on a given reaction zone at strain where unalloyed portion of fiber reaches its ultimate strength
$A_{r,i}$	area fraction of reaction zone at ultimate strength of fiber
$\sigma_f$	ultimate tensile strength of fiber
$A_f$	area fraction occupied by fiber

3. The tensile strength of alloyed tungsten fiber decreased with increasing penetration of the alloying element into the tungsten fiber. Chromium reacted tungsten fibers were found to be stronger than nickel reacted fibers since the penetration zones were much smaller and the alloy zone itself was believed to be much stronger.

4. Composites in which a brittle alloy zone was formed with the fiber and which resulted in low strength and brittle behavior of the composite at room temperature were observed to be more ductile at temperatures of approximately 300° F and above. The transition from brittle to ductile fracture also resulted in improved tensile strength.

5. The apparent ductility of the composites investigated varied with the type of fracture encountered. Large differences existed between the ductility of composite specimens as indicated by the reduction in area results obtained for the specimens as compared with the reduction in area values obtained for the fibers and matrix materials. The discrepancy results from gaps formed between the necked fibers and the matrix which occur because of a shear failure of the bond between the matrix and the fiber. When the matrix-fiber bond was strong enough to cause the fibers to bend inward following the contour of the necked region of the composite specimen, better agreement was achieved between reduction of area of the composite and the individual constituents.

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National Aeronautics and Space Administration,  
Cleveland, Ohio, August 2, 1965.

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