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ELECTRICAL RESISTIVITY AND CONDUCTIVITY OF TUNGSTEN-FIBER-REINFORCED COPPER COMPOSITES

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SUMMARY

Tungsten-fiber-reinforced copper composites with fiber contents from 14 to 75 volume percent were made by liquid-phase infiltration techniques. Electrical-resistance measurements of the composites, unreinforced copper, and tungsten wires were made by using a Kelvin bridge. The resistivity of the composites was found to follow a hyperbolic function with fiber content, and the conductivity was found to follow a linear relation with fiber content. The ratio of ultimate tensile strength to resistivity and the ratio of ultimate tensile strength/density to resistivity of the composites were found to be superior to available standard conductors and to show promise for applications requiring high-strength electrical conductors.

INTRODUCTION

In recent years, considerable interest has been generated in the field of fiber-reinforced metallic composites. This interest was stimulated by the prospect of developing engineering materials that utilize the high strengths available in metallic fibers by using them to reinforce metallic matrices.

Investigations conducted at the NASA Lewis Research Center (refs. 1 and 2) to determine the tensile properties of composites utilized a model system, tungsten fibers in a copper matrix, in which both components were mutually insoluble. The results of these investigations showed that the ultimate tensile strength, yield strength, and modulus of elasticity of the composites were proportional to fiber content.

As shown in these references, the tensile properties of a composite may be controlled through the proper selection and application of the properties of the components. Although many applications exist for the use of composite materials as structural members, many other specific applications also exist. One such objective is that of high-strength electrical conductors. For such an application the electrical resistivity and conductivity of the composite materials must be known.

The only results of the electrical properties of fiber-reinforced composites noted in the literature are reported in reference 3. In this work, composites were made in which copper or silver matrices were reinforced with fibrous felts of tungsten or other metals. The results obtained indicated a linear increase in resistivity with fiber content to the maximum fiber content tested (40 volume percent). Since, however, the components of these composites, tungsten wires and copper, are insoluble in each other, the electrical properties would be expected to follow the example of binary alloys such as Pb-Sn and Zn-Cd, which are cited in references 4 and 5. These alloys are mixtures of two phases, and the conductivities, not the resistivities, follow a linear relation with composition expressed in volume percent. Since copper and tungsten act as a mixture in a composite, the conductivity of tungsten-fiber-reinforced copper composites also might be expected to be a linear function of volume percent fiber.

This investigation determined the electrical resistivity and conductivity of tungsten-fiber-reinforced copper composites over a wide range of fiber contents for composites containing both continuous and discontinuous fibers and related these results to fiber content. This investigation also compares the properties of tungsten-fiber-reinforced copper composites with those of other electrical conductors to determine if these composites have potential for applications requiring high-strength electrical conductors.

MATERIALS, APPARATUS, AND PROCEDURE

Composite specimens were fabricated by using 5-mil-diameter tungsten wire (General Electric type 218CS) as the fiber and oxygen-free high-conductivity (OFHC) copper as the matrix. Some specimens were made by using continuous reinforcement in which the fibers extended the entire length of the specimen, while others were made by using discontinuous reinforcement in which fibers of 3/8- or 1/2-inch length were used. In both cases, the fibers were longitudinally oriented and uniformly distributed.

Liquid-phase infiltration was used as described in references 1 and 2. The wires were placed in ceramic tubes, copper was placed above the wires, and the entire assembly was heated to 2200° F for 1 hour in vacuum. The liquid-phase infiltration formed a continuous network of copper around the wires.

The composite bars were ground into cylindrical test specimens, and specific-gravity measurements were taken to determine the fiber content of each specimen. The electrical resistance of each specimen was determined by using a Kelvin bridge, as described in reference 6, and the resistivity and conductivity were calculated. A similar procedure was used on specimens of 5-mil-diameter tungsten wire, annealed at 2200° F for 1 hour in vacuum and unreinforced copper. The wires were annealed to duplicate the infiltration conditions.

RESULTS AND DISCUSSION

Relation of Resistivity and Conductivity to Fiber Content

The results of this investigation are given in table 1 and are plotted in figure 1. The resistivity curve shows a hyperbolic shape with the resistivities of the components of the composite as the end points. The conductivity curve shows a linear relation with the conductivities of the components as the end points. Based on the linearity of the conductivity curve in figure 1, the conductivity of tungsten-fiber-reinforced copper composites containing either continuous or discontinuous fibers can be expressed by the equation:

$$K_c = K_f V_f + K_m V_m \qquad (1)$$

which can also be epxressed as:

$$K_c = K_m + V_f(K_f - K_m) \qquad (2)$$

where K is the conductivity, V is the volume percent of each component, and c, f, and m are subscripts representing composite, fiber, and matrix, respectively. This relation may also be expressed in terms of resistivity:

$$\frac{1}{\rho_c} = \frac{1}{\rho_f} V_f + \frac{1}{\rho_m} V_m \qquad (3)$$

which can also be expressed as:

$$\frac{1}{\rho_c} = \frac{1}{\rho_m} + V_f\left(\frac{1}{\rho_f} - \frac{1}{\rho_m}\right) \qquad (4)$$

TABLE I. - ELECTRICAL RESISTIVITY AND CONDUCTIVITY OF TUNGSTEN-FIBER-REINFORCED COPPER COMPOSITES

Specimen number	Fiber length, in.	Fiber content, volume percent	Resistivity, $\mu\Omega$-cm	Conductivity, $1/\mu\Omega$-cm
C-1	Continuous	73.5	3.58	0.280
C-2	↓	72.4	3.53	.283
C-3		71.4	3.35	.298
C-4		68.9	3.36	.299
C-5		67.8	3.25	.308
C-6		66.3	3.30	.303
C-7		60.2	2.96	.338
C-8		59.9	2.94	.340
C-9		52.3	2.70	.371
C-10		51.7	2.67	.375
C-11		41.8	2.43	.412
C-12		41.2	2.46	.407
C-13		33.7	2.24	.447
C-14		22.8	2.09	.479
C-15		20.4	2.06	.486
C-16		18.5	2.02	.496
C-17		14.0	1.97	.509
C-18		13.7	1.98	.505
D-1	3/8	29.3	2.13	.469
D-2	1/2	42.9	2.54	.394
D-3	↓	36.1	2.39	.418
D-4		35.0	2.25	.444
D-5		33.3	2.36	.424
Copper	---	0	1.70	.588
Tungsten wire	---	100	5.66	.177

where ρ is the electrical resistivity.

Application of Tungsten-Fiber-Reinforced Copper Composites as High-Strength Electrical Conductors

Because of the high strength reported in references 1 and 2 and the relatively high electrical conductivity observed in this investigation, tungsten-fiber-reinforced copper composites may have potential as practical, high-strength electrical conductors (ref. 7). Generally, the higher conductivity materials are weak, and the stronger materials are poorer conductors; however, although the resistivity of tungsten wire is about three times that of copper, the tensile strength results of references 1 and 2 show that the strength of tungsten wire is about eleven times that of copper. Since an application as a high-strength conductor calls for a material that is a compromise between strength and conductivity, comparisons may be made on the basis of the ratio of ultimate tensile strength to resistivity and the ratio of ultimate tensile strength/density to resistivity.

Figure 2 presents comparisons of tungsten-fiber-reinforced copper composites, on a strength-to-resistivity basis with available standard conductors, aluminum and silver (ref. 8), copper, and aluminum cable, steel-reinforced (ACSR) composite conductors (ref. 9). The ACSR conductor is a composite in that strands of low-density, high-conductivity EC aluminum are reinforced by strands of relatively low conductivity steel of about the same diameter. This is a composite cable because it has two components; however, they are not bonded in any way and rely on the friction of stranding to allow the steel rods to give added strength to the cable. The ratio of strength to resistivity for tungsten-fiber-reinforced copper composites is plotted in figure 2 against fiber content. The data for composites plotted in this figure are based on the linearity of strength with fiber content (refs. 1 and 2) and the linearity of conductivity with fiber content

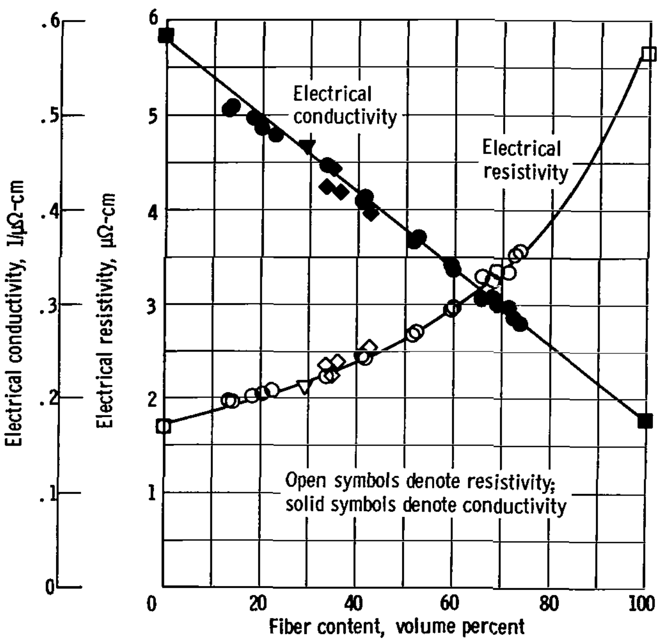

Figure 1. - Electrical resistivity and conductivity of tungsten-fiber-reinforced copper composites.

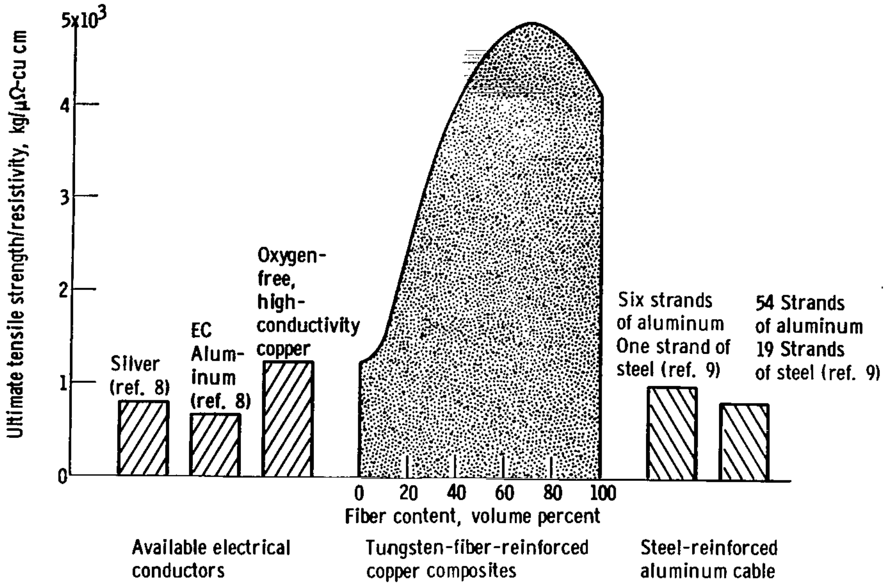

Figure 2. - Comparison of ratio of ultimate tensile strength to resistivity for tungsten-fiber-reinforced copper composites with other electrical conductors.

found in this investigation. Combining these two gives the equation used to calculate the ratio of tensile strength to resistivity:

$$\frac{\sigma_c}{\rho_c} = \sigma_c K_c = \left[\sigma_m^* + V_f(\sigma_f - \sigma_m^*)\right]\left[K_m + V_f(K_f - K_m)\right] \tag{5}$$

where σ_f represents the tensile strength of the fiber and σ_m^* represents the tensile stress on the matrix at the strain at which the ultimate tensile strength of the fiber is achieved. These calculations show that the strength-to-resistivity maximum is reached at a fiber content of about 70 volume percent. The figure shows that the ratio of strength to resistivity for the tungsten-fiber-reinforced copper composites increases rapidly above a fiber content of approximately 10 volume percent, reaches a maximum about 70 volume percent and then falls to that of the tungsten wire. The ratio of strength to resistivity for composites in the 50- to 75-volume percent fiber range is about three to seven times that of the other conductors.

For applications where density is important, the materials are compared on the basis of ultimate tensile strength/density to resistivity (fig. 3). The values for the ratio of ultimate tensile strength/density to resistivity were calculated by dividing equation (5) by the density of the composite, which is also a linear function of fiber content. The values were plotted from the following equation:

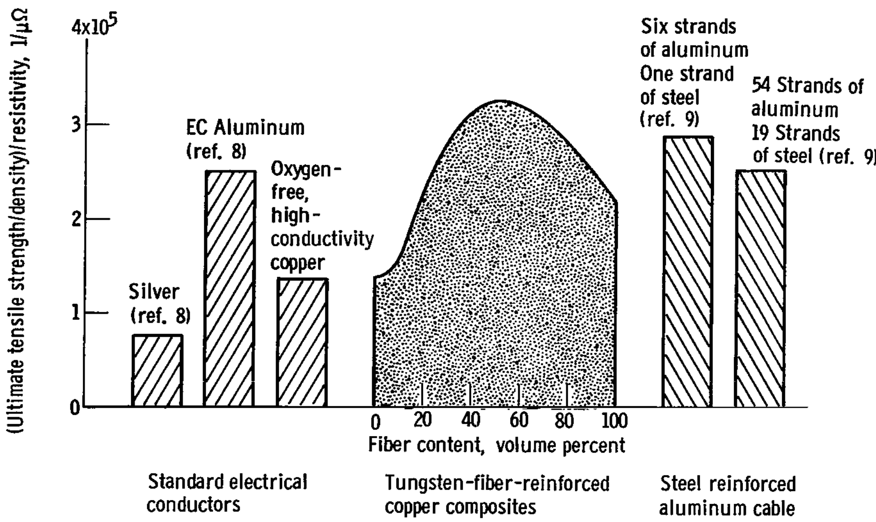

Figure 3. - Comparison of ratio of ultimate tensile strength/density to resistivity for tungsten-fiber-reinforced copper composites with other electrical conductors.

$$\frac{\sigma_c}{\rho_c D_c} = \frac{\sigma_c K_c}{D_c} = \frac{\left[\sigma_m^* + V_f(\sigma_f - \sigma_m^*)\right]\left[K_m + V_f(K_f - K_m)\right]}{\left[D_m + V_f(D_f - D_m)\right]} \tag{6}$$

where D is density. The ratio increases with increasing fiber content to about 50 volume percent and then drops to the value of the tungsten wire. The plot shows that for fiber contents of 50 to 60 volume percent the tungsten-fiber-reinforced copper composites are about 10 to 15 percent greater than the ACSR, about 30 percent better than aluminum, and more than twice as great as copper.

Certain assumptions were made in the calculations of the ratios of tensile strength to resistivity and tensile strength/density to resistivity. It was assumed that the reinforcing fibers were not stranded and that there was a uniform fiber content throughout the entire length. The calculations for the tungsten-fiber-reinforced copper composites were based on a model in which the fibers were axial and nonhelical and were bonded to the matrix. The calculations for the ACSR were based on the data presented in reference 9 in which the conductors, both steel and aluminum, were spiralled and unbonded. Thus, in the calculations of these ratios, the increase in resistance due to the additional length of the conductor required to form the spiralled cable and the strength reduction due to the cable configuration tend to reduce the ratios for the ACSR. The axial reinforcement, on the other hand, tends to reduce the conductor length and give a maximum strength to the tungsten-fiber-reinforced copper composites which tends to increase the ratios for these composites. These calculated ratios are presented as a first approximation to show the relative trends that might be expected; however, in an application as a high-strength electrical conductor, the actual design configuration used for tungsten-fiber-reinforced copper composites may influence the actual ratios obtained.

In the design of a high-strength electrical conductor, the cable must support its own weight. For conditions in which the support of its weight is of primary importance, the tungsten-fiber-reinforced copper composites show a significant increase in ultimate tensile strength/density to resistivity relative to available conductors. In many instances, however, externally applied loads, such as wind, ice, and foreign objects, which are not density dependent, must also be supported. Where external loads are important, the advantage of tungsten-fiber-reinforced copper composites over the other conductors becomes even greater, as shown by the ratio of strength to resistivity.

The plots in figures 2 and 3 also show that a fiber content of about 60 volume percent would be the best compromise between resistance, strength, and strength/density. Thus, from these considerations, composites of this type might have practical application as high-strength electrical conductors.

Application of Electrical Conductivity to Nondestructive Testing of Composites

A problem associated with testing composites has been the determination of fiber content prior to destructive testing. The results obtained in this investigation suggest that electrical conductivity may be used as a nondestructive test technique for the determination of fiber content for tungsten-fiber-reinforced copper composites. In addition, this technique allows a specimen to be scanned to determine areas of higher or lower fiber contents in the event of inhomogeneity of fiber distribution within the composite. Where solubility or reaction between the fiber and the matrix occurs, it may also be useful for determining the extent of interaction since the deviation from linearity may be an indication of the amount of alloying or penetration that has taken place.

SUMMARY OF RESULTS

The electrical resistivity and conductivity of tungsten-fiber-reinforced copper composites were determined by using a Kelvin bridge. The electrical and strength properties of the composites were compared with those of available electrical conductors. The following results were obtained:

1. The resistivity of tungsten-fiber-reinforced composites was a hyperbolic function of fiber content with the resistivities of the components as end points.

2. The conductivity of tungsten-fiber-reinforced copper composites was a linear function of fiber content with the conductivities of the components as end points.

3. The properties of these composites show promise as high-strength electrical conductors. The values of the ratio of strength/density to resistivity of tungsten-fiber-reinforced copper composites were higher than those of standard electrical conductors, and the values of the ratio of strength to resistivity were much greater.

4. Electrical conductivity may be useful as a nondestructive test technique for the determination of fiber content in tungsten-fiber-reinforced copper composites.

Lewis Research Center,
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Cleveland, Ohio, April 19, 1966.

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