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SUMMARY

An investigation was conducted to determine the stress-strain behavior and tensile properties of metallic composites and to relate them to the properties of the base materials. Room-temperature tensile and dynamic modulus tests were used to determine these properties. The composites were reinforced with either continuous or discontinuous fibers. The tensile properties and stress-strain behavior of composites reinforced with either type of fiber were similar, and in both cases the full strength of the fiber was utilized.

Four stages of deformation occurred during the tensile test. Two linear portions of the stress-strain curves were observed, primary and secondary; the slopes of both were a linear function of fiber content. The ultimate strength of the composites was also found to be a linear function of fiber content. Elongation at fracture decreased with increasing fiber content. This was accounted for in a postulated failure mechanism in which the fibers break at random points of weakness and an accumulation of random failures resulted in failure of the composite.

INTRODUCTION

The advance of technology is dependent, to a great degree, upon the development of improved structural materials. To meet these demands, considerable effort is being directed toward the creation of composite materials. Many future materials needs may be met by the use of fiber-reinforced composites in which a ductile, relatively weak matrix is reinforced with high-strength fibers. By far, the greatest success in this field has been in the reinforcement of plastics with fiber glass or similar material. Much of the research associated with the fundamentals of fiber reinforcement has also been in the field of glass-reinforced plastics. For example, statistical studies relating the strength of bundles of fibers to the strength of individual fibers has been made in reference 1. Studies of the effects of defects in glass fibers and such structural parameters as length to diameter ratio of full length and discontinuous fibers have also been made (ref. 2). Of particular interest is the relation, in mathematical equations, of the strength of glass-plastic composites to the strength of the components of the composite (ref. 3).

Some of the principles of reinforcement developed for fiber-glass reinforced plastics may be applicable to metallic composites. Research has been done on metal-fiber-reinforced metallic composites (refs. 4 to 7); however, the purpose of these programs was to develop strong materials rather than to investigate the fundamentals of reinforcement. Such materials as steel wool and kinked and crimped fibers have been used to strengthen matrices. Increases of as much as five times the strength of the unreinforced matrix have been noted for composites reinforced with ceramic whiskers (refs. 8 and 9). Summaries of much of this work have been published in references 10 and 11.

The study of fundamentals of reinforcement of metallic systems has been limited. Reference 12 contains a study of the effect of interfiber spacing and its relation to the properties of composites. The work done at the Lewis Research Center (refs. 13 to 15) involved the making and testing of composites composed of a fiber, tungsten, and a matrix, copper, which were insoluble in each other. An equation was presented that showed the relation between the ultimate tensile strength of the composites and the strengths and relative volume percents of the components. Not only was the equation verified experimentally for composites that contain fibers which extend the full length of the specimen, but it was also shown to be valid for composites that contain short length or discontinuous fibers.

Since the publication of the preliminary results (refs. 13 to 15), additional data have been obtained. It is the objective of this report to present these additional data as well as analyses of the stress-strain behavior and the mechanics of deformation of uniaxially oriented, fiber-reinforced metallic composites in which the components are mutually insoluble. A further objective was to relate the modulus of elasticity and the tensile properties of the composites to the fiber content and the properties of the components.

Composites were made with copper as the matrix and 3-, 5-, or 7-mil-diameter tungsten wire as the reinforcing fiber. In specimens of this type, the reinforcing fiber extended the full length of the composite test specimen. Composites were also made with 5-mil-diameter discontinuous reinforcement. Room-temperature tensile tests were conducted on the composites; stress-strain curves were obtained; and ultimate tensile strengths and elongations were measured. The modulus of elasticity was also determined by using dynamic testing methods. The data obtained were used to analyze the stress-strain relations as well as the strengthening and failure mechanisms of fiber-reinforced metallic composites.

MATERIALS, APPARATUS, AND PROCEDURE

Materials Selection

Commercially obtained, drawn tungsten filament wire (General Electric type 218CS), of 3-, 5-, and 7-mil diameter was selected as the reinforcement for the composites in this investigation because of its high tensile strength, high recrystallization temperature, availability in a wide range of diameters, and relative ease of handling.

High-purity copper (99.994 percent Cu) was selected as the matrix material for composites in this investigation because it met the following requirements: a melting point below a temperature where the properties of the tungsten fiber are seriously reduced, insolubility in tungsten (ref. 16), and ability to wet tungsten (ref. 17).

Specimen Preparation

Composites reinforced with continuous fibers. - These composites were prepared by liquid-phase infiltration. The fibers were placed in ceramic tubes and infiltrated with copper. This method assured axial orientation. Some specimens were infiltrated by placing a piece of copper, the surface of which had been cleaned in an acid-dip solution (H_2SO_4, HNO_3, HCl, and water), below the fiber bundle and melting it. Another method consisted of placing the infiltrant above the fiber bundle. In either case, the entire assembly was heated to 2200° F and held at that temperature for 1 hour in either a vacuum or a hydrogen atmosphere.

After infiltration, the specimen rods were removed from the ceramic tubes. Some of the rods were made into tensile specimens by silver-soldering grips onto them, while others were ground to shape. Examples of these specimen configurations are shown in figure 1.

Composites reinforced with discontinuous fibers. - Chopped lengths of tungsten wire, 3/8 inch long, were loaded into ceramic tubes of 1/8-inch diameter and infiltrated with copper by means of the top-feeding technique described previously for continuous reinforcement. The rods were made into tensile specimens by silver-soldering grips onto them.

Tensile Tests

Room-temperature tensile tests were made by using an Instron tensile testing machine. A constant crosshead speed of 0.10 inch per minute was used for all tests. Specimens that failed near the grips were discarded. The load measurement was made by a load cell and was independent of the type of strain measurement used.

Two methods were available to measure strain. In the first method, elongation was measured from the movement of the crosshead. All data on fibers, as well as preliminary results on composites (refs. 13 to 15) were obtained in this way. In the second method, strain was determined with a Baldwin T2M extensometer attached to the specimen. The output signal was fed into an X-Y recorder. This equipment was limited to a maximum strain measurement of 2.0 percent for a 1-inch gage length and had an accuracy of about 0.03 percent strain.

Measurement of elongation of specimens after fracture was difficult because of the jagged nature of the fracture surfaces. Specimens could not be put back together accurately enough to permit precise measurement of the total elongation.

Because of this, it was necessary to measure the total elongation from the crosshead movement.

Yield strength was determined from the stress-strain curves for some composites reinforced with 5-mil-diameter fibers by using the 0.2-percent offset method.

Tungsten fibers. - Tungsten fibers, in the as-received and heat-treated condition, were attached to aluminum gripping tabs with sealing wax and tested in tension. The effects of exposure to different infiltration temperatures upon the strengths of the fibers was determined. Fibers were annealed for 1 hour at temperatures ranging from 1500° to 2500° F and tested in tension at room temperature. The infiltration temperature of 2200° F was chosen on the basis of these data as well as on preliminary experiments to determine the fluidity of the copper matrix.

Copper. - To determine the tensile properties of the copper matrix used in the composites, tensile tests were conducted on vacuum-cast copper rods, which had been annealed for 4 hours at 1800° F in vacuum. Tensile specimens were then machined and tested in the Instron at a crosshead speed of 0.10 inch per minute.

Composites. - Room-temperature tensile tests were made on composites reinforced with continuous or discontinuous fibers. Cross-sectional area and volume-percent reinforcement data for some composite specimens were obtained by sectioning the failed specimen transversely in an area immediately adjacent to the fracture but outside the necked region. The sections were mounted, polished, and photographed. Planimeter measurements and a wire count were obtained from the photographs, and cross-sectional area and volume percent fiber were calculated. Other specimens were measured with a micrometer. The volume percent fiber was determined either by a wire count or by a specific-gravity measurement.

Dynamic Modulus Testing

The resonant frequencies of rods of copper, tungsten, and composites were measured by sonic methods. Resonances were induced in the flexural mode of vibration. The modulus of elasticity was calculated from the resonant frequency obtained. Since cylindrical specimens of different lengths and diameters were used in this portion of the investigation, correction factors were necessary. Appropriate length to diameter corrections were based on the equations of reference 18, as solved and tabulated in reference 19. Dynamic testing methods were chosen because of the greater sensitivity of this method over static methods and because the stress levels applied in this method were well below the elastic limit of either material. Good agreement between the room-temperature moduli obtained dynamically and those obtained statically has been demonstrated by others (refs. 20 and 21).

RESULTS

Tensile-Test Results

The results of room-temperature tensile tests, conducted on 3-, 5-, and

7-mil-diameter fibers annealed at temperatures up to 2500° F, are shown in figure 2. The curves show the effects of exposure to these temperatures for time periods of 1 hour in vacuum. The strength and elongation have been reduced. Essentially the same properties were obtained from wires that had been annealed in hydrogen at 2200° F.

From these curves it can be seen that exposure to a temperature of 2200° F for 1 hour reduces the strength of the 3-, 5-, and 7-mil-diameter fibers to about 331,000, 327,000, and 290,000 psi, respectively. Since all composites were infiltrated at 2200° F, these strengths were considered to represent the strength of the fibers throughout this study.

The average ultimate tensile strength of the annealed copper used as the matrix in this investigation was 27,800 psi and represented the average of eight tests.

The results of room-temperature tensile tests on composites that contain several volume percent of fiber are tabulated in table I(a) for composites reinforced with continuous 3-, 5-, or 7-mil-diameter fibers. These results are plotted as a function of composition in figures 3(a) to (c). They include data previously reported in references 13 to 15 as well as additional data more recently obtained. The line shown on each curve represents a prediction of tensile strength as a function of composition. The calculation of this line was explained in references 13 to 15, and further discussion will be presented later. The strengths of composites show good agreement with the calculated line and are proportional to the volume percent reinforcing fiber present. The tensile strengths of composites reinforced with different wire sizes show the same trends.

The same trends may be seen in figure 3(d) and table I(b) for composites reinforced with short length, discontinuous 5-mil-diameter fibers. Again, both the table and the figure represent both old and new data. The line shown in this figure (fig. 3(d)) is a calculated line and is identical to that used for the 5-mil-diameter continuous-fiber-reinforced composites shown in the previous figure (fig. 3(b)). Good agreement of the data with the calculated line may be seen.

A plot of percent elongation, at failure, of composites reinforced with 5-mil-diameter continuous fibers, plotted as a function of volume percent fiber as well as that of tungsten wire and copper, is shown in figure 4. The measurements were made from the crosshead movement of the Instron. The fracture elongation decreases with increasing fiber content. While the fibers alone exhibit from 1.3 to 2.9 percent elongation at failure, the composites show a much greater elongation.

Stress-strain curves for copper, tungsten wire, and several composites reinforced with different percentages of 3-, 5-, and 7-mil-diameter wire are shown in figures 5(a) to (c). The data curves shown for the tungsten wire of the three sizes used were taken from the crosshead motion of the Instron. These curves were then corrected for machine deflection and replotted. The strains shown in the stress-strain curves for the composites were measured by an extensometer. These stress-strain curves show an early transition into plastic flow of the copper at a very low strain. The tungsten wire exhibits elastic behavior for about 0.4 percent strain, while the composites show a linear slope to about the same strain. The ultimate tensile strength of the fiber was reached at about 1.4 percent strain. The composites also show their ultimate strength at approximately the same strain. Although the ultimate tensile strength of copper is about 27,800 psi, figures 5(a) to (c) show that the stress on the copper is only about 8000 psi at 2-percent strain. The slope of the plastic flow portion of the stress-strain curve for copper is about 0.2×10^{6} psi over the range covered in these figures.

The stress-strain curves for a 5-mil-diameter tungsten wire, copper, and a discontinuous-fiber-reinforced composite that contains 5-mil-diameter wire are presented in figure 5(d). This figure shows the same general trends shown in the previous figures for continuous-fiber-reinforced composites.

An enlargement of the low-strain region of the stress-strain curves for copper, tungsten, and the composites is shown in figure 6. It can be seen that the copper is undergoing elastic strain for only about 0.03-percent strain. Beyond this point, it is straining plastically. Composites reinforced with continuous fibers of different diameters and 5-mil-diameter discontinuous fibers show a change in slope in their stress-strain curves near this 0.03-percent strain. Above this strain, the slope of the stress-strain curve for each composite is reduced. The strain at which the change in slope occurs varies from specimen to specimen, and this is probably due to a lack of sensitivity of the extensometers in the very narrow region of elastic strain. The slope of the stress-strain curve before the change occurs may be termed the initial modulus of elasticity, while the slope afterward may be termed the "secondary modulus".

The slopes of the secondary linear portions of the stress-strain curves obtained with the extensometer from specimens of 3-, 5-, and 7-mil-diameter continuous-fiber-reinforced composites and 5-mil-diameter discontinuous-fiber-reinforced composites are plotted in figure 7. A least squares fit of the data, as shown by the line in the figure, has an intercept of 56.0×10^{6} psi at 100 percent tungsten and about 0.9×10^{6} psi at the copper intercept. This figure shows the slopes of the secondary linear portions of the stress-strain curves of composites reinforced with fibers of different diameters, as well as composites reinforced with discontinuous fibers, fall along the same line.

Yield Strength Results

Results of yield strength determinations for composites reinforced with various amounts of continuous 5-mil-diameter tungsten fibers and plotted as functions of fiber content are depicted in figure 8. These results were obtained by means of the 0.2-percent offset method.

Dynamic Modulus Results

The results obtained from measurements of the dynamic modulus of elasticity on specimens reinforced with continuous fibers are tabulated in table II(a) and plotted in figure 9(a). Data for specimens reinforced with discontinuous fibers are tabulated in table II(b) and plotted in figure 9(b). At the same volume percent fiber, the moduli are essentially the same. A dynamic modulus of 58.8×10^6 psi was obtained in this investigation for a 0.125-inch-diameter tungsten rod; this compares favorably with the values found in the literature for tungsten, which range from 50.0×10^6 to 59.8×10^6 psi (refs. 21 to 28). The static modulus of a 10-mil-diameter tungsten wire was found to be 58.0×10^6 psi (ref. 28). Modulus of elasticity values reported for annealed copper range from 13.4×10^6 to 18.9×10^6 psi (refs. 29 to 31), while a dynamic modulus of 17.7×10^6 psi and an average static modulus of 18.1×10^6 psi was found in this investigation.

Metallographic Results

Figure 10 shows a transverse cross section of a typical copper-tungsten composite reinforced with about 70-volume-percent of 5-mil-diameter fibers. The fibers are evenly distributed throughout the matrix and are oriented parallel to the tensile axis. The interfiber spaces are filled with copper.

It can be seen from figure 11, an electron photomicrograph of a transverse section of a composite showing the tungsten-fiber - copper-matrix interface, that there is no recrystallization of the grains at the periphery of the fiber. Also, there are no void areas at the interface, and the copper matrix has apparently wet the surface of the tungsten fiber.

A fracture edge of a composite is shown in figure 12. Necking of both the fibers and the composite occurred at the fracture edge. Some fibers broke at random points along their length, away from the fracture edge. Higher magnifications of these random location breaks have shown necking of the fibers.

DISCUSSION

Tensile Behavior of Fiber-Reinforced Composites

In this investigation, fiber-reinforced composites were studied that were composed of two mutually insoluble materials each retaining its individual identity. The fiber reinforcement was uniaxially oriented in a direction parallel to the tensile axis. In this type of composite, each of the two phases retained its individual stress-strain characteristics. The stress-strain behavior observed for the composites studied will subsequently be analyzed. Prior to the description of the behavior of the composites, the following postulated stages of deformation should be considered:

Stage I - Elastic deformation of fiber; elastic deformation of matrix

Stage II - Elastic deformation of fiber; plastic deformation of matrix

Stage III - Plastic deformation of fiber; plastic deformation of matrix

Stage IV - Failure of fiber and matrix

In preliminary studies (refs. 13 to 15) the authors showed that the tensile strength of composites of copper reinforced with continuous or discontinuous tungsten fibers was a linear function of fiber content and could be represented by the following equation:

$$\sigma_c = \sigma_f A_f + \sigma_m^* A_m \tag{1}$$

where the mainline symbols are defined as

A area fraction or volume percent when unity length is considered and $A_f + A_m = A_c \equiv 1$

σ tensile strength

σ_m^* stress on matrix, taken from stress-strain curve, at an equivalent strain to that at which the ultimate tensile strength of fiber is achieved

and the subscript symbols are defined as

c composite

f fiber

m matrix

These previous studies discussed only stage III behavior, and the use of equation (1) was limited to the prediction of the ultimate tensile strength of composites, and made no attempt to predict the behavior of composites at any other value of strain.

Data obtained since the publication of these preliminary results confirm the results previously reported. These data, as well as additional work on the behavior of composites undergoing stages I, II, and IV of deformation, are presented in this report.

Generalized equation for predicting stresses in fiber-reinforced composites. - Analysis of these other stages of behavior shows that equation (1) may be modified slightly to a more general form to allow the prediction of the stress or a composite at any value of strain,

$$\sigma_c^* = \sigma_f^* A_f + \sigma_m^* A_m \tag{2}$$

The σ^*'s used in equation (2) represent stresses at that particular value of strain taken from the stress-strain curves of the components of the composite, in the condition in which they exist in the composite. The four stages of tensile behavior in a fiber-reinforced composite will now be discussed as well as forms of the general equation pertaining to those stages.

Stage I - Elastic deformation of fiber; elastic deformation of matrix. - Upon loading a composite specimen in a tensile test, the initial strain observed is elastic for the fiber, the matrix, and the composite. A mathematical expression for this behavior may be obtained by using equation (2) with the modifications that the stresses taken from the stress-strain curves, when divided by equal elastic strains, represent the initial modulus of elasticity. Thus, the initial modulus of elasticity of a fiber-reinforced composite may be expressed by the following equation:

$$E_c = E_f A_f + E_m A_m \tag{3}$$

where E is the initial modulus of elasticity.

Equation (3) predicts that the initial modulus of elasticity of a composite should be a linear function of fiber content. Figure 9 shows plots of modulus of elasticity as a function of fiber content for composites reinforced with either continuous or discontinuous fibers. A straight line relation exists. The lines shown were obtained by using the dynamic moduli of the two components as end points. Data obtained for the composites is in good agreement with the values predicted by using equation (3). The dynamic modulus data obtained for the components show good agreement with published values.

Stage II - Elastic deformation of fiber; plastic deformation of matrix. - The plots of initial modulus of elasticity as a function of volume percent fiber shown in figure 9 were obtained by using data from dynamic tests, as described earlier. To analyze stage II behavior, it is necessary to examine the stress-strain curves of the composites and their components at strains larger than those representing only the elastic behavior of the least elastic component. This type of analysis is necessary because the two materials comprising the composite do not deviate from elastic behavior at the same strain.

Figure 6 shows that the copper deviates from proportionality at about 0.03-percent strain. Below this strain, both components are acting elastically; however, beyond this strain, the copper is acting plastically. The figure also shows a change in slope for all the other stress-strain curves representing the composite specimens. This change in slope has been observed in fiber-glass-reinforced plastics (ref. 32). (As mentioned earlier, the names initial modulus and secondary modulus have been applied to these slopes.)

Below this slope change, the composites are undergoing initial elastic behavior, as described by stage I deformation. Above these strains, the slope of the copper curve is almost flat. The copper is contributing very little to the load-carrying capacity of the composite, and the tungsten is carrying a much greater percentage of the load than previously carried when the copper was elastic. This gives rise to a secondary elastic behavior of the composite, since the small portion of the load carried by the plastic copper is masked by the behavior of the tungsten. The slope of this secondary elastic portion of the curve of the composite is lower than the slope of the initial elastic portion, since the slope of the stress-strain curve for the copper in the composite has been reduced from 17.7×10^6 psi in the elastic portion of the curve to about 0.2×10^6 psi in the plastic portion.

Figure 7 shows a plot of the secondary moduli of composites as a function of fiber content. The line shown is a least squares fit of the data. This curve shows that a linear relation exists between the secondary modulus and the fiber content. The behavior could be expressed by the following form of the general equation:

$$E'_c = E_f A_f + \left(\frac{\sigma_m^*}{\epsilon}\right) A_m \tag{4}$$

where

E'_c secondary modulus of elasticity of composite

$\frac{\sigma_m^*}{\epsilon}$ slope of stress-strain curve of matrix at a given strain ϵ beyond proportional limit of matrix

To determine whether deformation in this stage was elastic or plastic, several specimens were tested by loading to a strain where the copper should have behaved plastically, while the tungsten remained elastic. The load was then removed. A typical stress-strain curve obtained under these conditions shows an initial linear slope (fig. 13) as predicted by equation (3), a change in slope, and a second linear slope corresponding to the secondary modulus of elasticity. Loading was then stopped. The decrease in load noted in the curve, with no accompanying change in strain, does not reflect the behavior of the specimen itself but is due to a relaxation in the servomechanism circuit of the testing machine (private communication from R. A. Heinrich of Instron Engineering Corp.) This relaxation was noted for tests on specimens of copper and steel rods as well as composites.

During unloading, the composite specimen contracted. The initial slope of the unloading curve appeared to be parallel to the initial elastic slope during loading. Thus, the first contraction was elastic in character. A change in slope was also noted on unloading. For the remainder of the curve to zero load, the slope appeared to be almost parallel to the secondary elastic portion of the loading curve. A small amount of permanent set appeared to be retained in the specimen after the loading-unloading cycle. If the load-relaxation of the servomechanism is compensated for, the permanent set is reduced but still is present.

In conventional materials, when the load is released, all the contraction is elastic, regardless of whether the material had been deformed plastically or elastically. In copper-tungsten composites, the initial contraction appears to be elastic, but after a small increment of elastic contraction, the remaining contraction is what might be called secondary elastic behavior and a change in slope is noted in the curve. This second portion of the curve indicates that, as on loading, the tungsten fibers are acting elastically, while the copper behaves plastically. The elastic force on the fibers exerts a compressive force on the copper matrix and plastically contracts the copper, but this elastic force is not strong enough to cause the composite to recover completely. Eventually the compressive force in the copper balances the elastic tensile force in the fibers. Because of this, the composite cannot return to zero strain, and it shows a small amount of permanent set during cyclic loading.

The occurrence of the initial and secondary elastic behavior observed in the tungsten-copper system would probably be observed in other types of fiber-reinforced composites in which the fiber and the matrix deviate from elastic proportionality at different strains. If the deviation occurs at the same strain, then there would be a direct transition from initial elastic behavior into plastic flow. On the other hand, the greater the strain between the proportionality deviations of the fiber and the matrix, the longer the strain range over which the secondary behavior would occur. The secondary modulus observed in this investigation was easily determined because of the linearity of the slope of the plastic flow stress-strain curve over a range of strain. In the case where a matrix material had a constantly changing or fast work-hardening slope in the early stages of plastic flow, there would probably not be a constant secondary modulus; however, in the case of a metal with a linear slope, such as copper, the secondary modulus would exist and may be more useful as a design parameter than the initial modulus.

Stage III - Plastic deformation of fiber; plastic deformation of matrix. - With increasing strain, both components of the composite pass into plastic flow. The stress-strain curves presented in figure 5 show that the ultimate tensile strengths of the composites and fibers were achieved at about 1.2- to 1.6-percent strain. These stress-strain curves also show that the stress on the copper specimens at 1.3-percent strain is about 8000 psi and does not increase significantly over the range of strain plotted in these figures. This value was used as σ_m^* in equation (1). The data on the strength-composition curves shown in figure 3 show good agreement with this equation.

Since the ultimate tensile strength of the copper with no fibers present is 27,800 psi, then at some very low fiber content, where the matrix is the major load-carrying component, any fibers present would not contribute substantially to the strength of the matrix, and after the fibers had broken, the matrix would continue to strain and finally reach its ultimate tensile strength as if no fibers were present. Although no data has been obtained for composites containing such very low fiber contents, calculations were presented in references 13 to 15 to allow the prediction of the tensile strength of composites in this region and also to predict the fiber content below which effective reinforcement would not take place.

In addition to tensile strength, yield strength was also determined by means of the 0.2-percent offset method. Figure 8 shows a plot of such data obtained for composites, copper, and tungsten. The data was obtained from stress-strain curves. It is evident that a linear relation exists here also. Thus, the discussion previously made for the ultimate tensile strength should also pertain to the yield strength of composites.

The determination of yield strength in tungsten-fiber-reinforced copper composites is complicated by the fact that there are two linear portions of the stress-strain curve. Since in the determination of yield strength a line that is offset 0.2 percent and parallel to the slope of the linear portion of the curve is used, two yield strengths (initial and secondary) are obtained depending upon which slope is used. The difference between the two values obtained will decrease with increasing fiber content. Because of the small increment of strain over which initial elastic behavior occurs, the yield strength obtained through conventional means may be missed entirely unless very sensitive instrumentation is used. Therefore, for composites it may be more practical to use the slope of the secondary elastic behavior, since it covers a much wider range of strain and is more easily measured. This is the case for tungsten-fiber - copper-matrix composites and may also be applicable to other systems. From the practical viewpoint of composite applications, this secondary yield strength probably has much more engineering significance than the initial yield strength. The yield strength determined by means of the 0.2-percent offset method parallel to the secondary slope is plotted in figure 8 as a function of composition. A linear relation exists between yield strength and fiber content.

Stage IV - Failure of fiber-reinforced metallic composites. - This stage of the deformation of tungsten-fiber-reinforced copper composites occurs after the composite has reached its ultimate strength. Stress-strain curves (fig. 5) show that the stresses on the composites and the fibers reach a maximum and then gradually drop off to failure. Elongation is plotted to a 2-percent strain. Figure 4, however, shows a plot of percent elongation at failure as a function of fiber content. While the fibers alone exhibited from 1.3- to 2.9-percent elongation at failure, the composites show a much greater elongation.

This additional strain at failure could be explained by a comparison to discontinuous-fiber-reinforced composites. A broken fiber could be considered analogous to a discontinuous fiber and could continue to support a portion of the total load, transferring its portion of the load across the broken ends of the fiber through the matrix by a shear mechanism. It is postulated that, with increasing strain, after the fracturing of the first fiber occurs, other fibers continue to break at random locations. Metallographic evidence seems to verify these concepts. Figure 12 shows the fracture edge of a composite. Necking of both the individual fibers and the composite has occurred at the fracture edge, while some fibers have broken at random points along their length away from the fracture edge. Higher magnification examinations of the random location breaks also showed necking of the fibers at these breaks. It might be of interest to note that audible sounds could be heard emanating from the composites as the fibers break progressively. In addition, one tensile test was conducted in which the load was adjusted so as to give a greater sensitivity in the region of fracture. The curve obtained from this test showed jagged and irregular serrations indicating that many fibers were breaking as strain continued.

Eventually, a localization of random fiber breaks would occur in a given cross section, and the remaining fibers at this cross section would then fail. In specimens that contain large percentages of matrix materials, appreciable elongation could occur after the fibers in a cross section fail. At this point, the load on the specimen is impressed entirely upon the matrix. The amount that the matrix continues to strain after fracture of the reinforcing fibers depends upon the amount of matrix material remaining. If sufficient matrix material were present, elongation would continue as if no fibers were present, since only the matrix would be straining. If the matrix content were low, only a small additional amount of strain would occur before the specimen would fail.

It should be noted at this point that good bonding of fiber to matrix is essential to cause the delayed fracture of the composite. Many applications of composites might be envisioned where delayed fracture would not be of concern, and hence continuous fiber-reinforced specimens would not necessarily require a bonding of the matrix to the fiber in the test section.

Up to the failure of the first fiber, the primary purpose of a matrix in a continuous-fiber-reinforced composite is to provide a binder to join the fibers together and allow them to be made into a shape in which the properties of the fiber may be utilized in a stress-carrying member. Matrices could also be alloyed to give the composite such useful characteristics as corrosion resistance and ductility both during fabrication and use.

The matrix becomes an important consideration in stage IV behavior of continuous-fiber-reinforced composites. First, a bundle of fibers will be considered in which there is no matrix present. In a study of a bundle of fibers (ref. 1), a statistical analysis of the tensile strength of bundles composed of a number of fibers of equal lengths is described. The fibers were considered to be clamped in such a manner that all the fibers, when loaded, would have an equal elongation. In this situation there could be no interaction of one fiber with another in the test portion of the bundle. The results of this mathematical analysis indicated that the average tensile strength of the bundle would be less than the average strength obtained for the individual fibers making up the bundle. The greater the amount of scatter in the strength of the individual fibers, the lower the total strength of the bundle.

The incorporation of a bundle of fibers into a matrix to form a composite modifies the behavior of the bundle, since, in this situation, there is an interaction between fibers through a shear bond with the matrix. Reductions in the strength of fibers bonded by copper were not observed in the investigation described herein. In fact, it was shown that the average strength of the fibers was achieved in the composites as is revealed by the strength-composition diagrams (fig. 3). The premature fracturing of the weakest fibers did not reduce the strength of a composite, since the matrix transferred the load around the broken ends of these fibers.

For composites reinforced with continuous fibers, the principal requirement, which must be met by the matrix material, is ductility if adequate bonding is assumed. The material must exhibit sufficient ductility to allow both the composite to withstand shock and impact and the fibers to reach their full strength. In the case of fibers such as tungsten, which show some plastic flow, the matrix must undergo sufficient strain to allow the tungsten fiber to reach its ultimate strength.

Strengthening Mechanism of Discontinuous-Fiber-Reinforced Composites

Although the stress-strain behavior and tensile strength observed for discontinuous-fiber-reinforced composites is similar to those observed for composites with continuous reinforcement, the mechanism by which such composites are strengthened is different. The bond strength in a continuous-fiber-reinforced composite was shown to be of most importance subsequent to the failure of the first fiber. In the case of discontinuous-fiber reinforcement, however, a bond between the matrix and the fiber is essential during all stages of deformation. The mechanism by which the fiber contributes its strength to a composite is a shear mechanism, as described previously for metallic composites (refs. 13 to 15) and for fiber-glass-reinforced plastics (refs. 33 and 34). A schematic model of this type of composite is shown in figure 14. The discontinuous fibers in the composite are alined parallel to each other and to the tensile axis. It is assumed that the fibers overlap each other by varying amounts and that they are individually bonded to the matrix.

Even if the bond between the discontinuous fiber and matrix is weak, enough shear stress can be applied to the fiber to cause it to fail in tension, rather than shearing out of the matrix, if the fiber is long enough. Thus, for a given pair of materials, the length of fiber that is bonded to the matrix must be sufficient to support a shear stress that is equivalent to the tensile stress on the fiber. Equating the shear load on the bond to the tensile load necessary to cause failure of the fiber permits the calculation of a so-called critical length-to-diameter or aspect ratio, as shown in the following equation:

$$\frac{L}{D} = \frac{1}{4}\frac{\sigma_f}{\tau} \tag{5}$$

where

D diameter

L length

σ_f tensile strength of fiber

τ shear strength of fiber-matrix interfacial bond

Solution of this equation, with the assumptions and values mentioned in references 13 to 15, resulted in a critical aspect ratio of 16 for tungsten fibers and a copper matrix.

For a 5-mil-diameter tungsten fiber in a copper matrix, a length of approximately 80 mils would be necessary to support a sufficient shear load. Although it was not the objective of this investigation to get an exact determination of the critical aspect ratio, the results obtained do show that the average aspect ratio of 75 (L/D = 0.375/0.005), which was used, was more than sufficient to support the tensile load in the fibers and to cause the composites to fail by tensile fracture of the fibers. The subjects of bonding and aspect ratio will be treated in more detail in the following section.

Factors Influencing the Properties of Fiber-Reinforced Composites

Many types of fiber-reinforced composites have been made and studied, but most of the research has been in the field of fiber-glass-reinforced plastics.

Consequently, most of the concepts dealing with the mechanisms of reinforcement have been developed for this type of composite. Perhaps one of the greatest problems associated with the understanding of the strengthening mechanism is that, although much of the work on these different systems is interrelated, there are many situations that do not permit the generalization and extrapolation of the concepts from one system to another.

It is the purpose of this portion of the discussion to mention some of the factors influencing the strength of both continuous- and discontinuous-fiber-reinforced composites. Some of the generalizations made will be applicable to both types, while others will not.

Bonding and aspect ratio. - Much consideration has been given in the literature to the problem of bonding the fiber to the matrix. Bonding is much more critical for composites reinforced with discontinuous fibers than for those with continuous reinforcement. In discontinuous-fiber-reinforced composites, there must be a good bond between the fiber and the matrix to allow the load to be transferred from one fiber to another. The quality of such a bond is reflected by the critical aspect or length-to-diameter ratio. Much has been written about aspect ratio, which is a ratio of the fiber length that is required for the fibers to reinforce the matrix to the diameter of the fiber. The weaker the bond, the greater this ratio. Thus, the critical aspect ratio, or critical length-to-diameter ratio, is a manifestation of the shear length necessary to transmit a load from the fiber to the matrix or vice versa and allows the fiber to reach its full tensile strength in a composite.

The concept of critical aspect ratio may be further complicated by the interfiber spacing. Movement of the matrix relative to the fiber at the fiber-matrix interface could be restrained by the bond. As the distance from the interface is increased, the effect of this restraint would be reduced. Thus, there may be the possibility that the aspect ratio for a given fiber diameter may be lowered at high volume percentages of fiber and may increase at lower fiber contents because of the changes in the interfiber spacing.

Reference 2 reports an investigation on the effect of aspect ratio on strength and the development of what might be called a length-strength relation. This relation was based on the fact that the number of defects in a glass fiber increased with increasing fiber length, and as the defects were removed by fracturing, the resulting segments were stronger as the length decreased. This process continued until the fibers became shorter than the critical length, at which time the composite failed because of interfacial shear. It is pointed out in references 33 and 34 that aspect ratio is further complicated by variations in tensile and shear stresses along the length of the fiber.

It is evident that the critical aspect ratio for discontinuous-fiber-reinforced-composites is difficult to analyze. The work on fiber-glass-reinforced plastics reported in reference 2 indicates that an aspect ratio ranging from 400 to 1000 would be necessary for reinforcement depending upon the strength of the fiber (ref. 2). The work at the Lewis Research Center of NASA has shown that a ratio of 75 was more than sufficient to provide efficient reinforcement in a metal-fiber - metal-matrix composite. This shows that, although the mechanism of bonding of the tungsten-fiber-reinforced copper composites is probably similar to glass-fiber-reinforced plastics, the materials involved and the properties of the bond are different, as reflected in the aspect ratios needed for reinforcement.

Scatter of tensile strength of fibers. - The more likely a material is to have flaws and defects, the greater is the likelihood for scatter in tensile properties. Considerable scatter has been observed in the tensile properties of such fibers as glass and whiskers, and this scatter can probably be attributed to defects. Although drawn metallic fibers may contain defects, generally they are not as notch-sensitive as glass but do exhibit greater ductility.

Both glass and tungsten fibers show considerable scatter in elongation at failure; however, the scatter in strength is much less for the metallic fiber because glass fibers exhibit elastic behavior to fracture when tested in tension. Thus, any scatter in strain is accompanied by a directly proportional scatter of stress. This behavior is shown in the schematic stress-strain curve presented in figure 15(a). The strength of a glass fiber that breaks at 2.8-percent strain is twice as great as one that breaks at 1.4 percent. Composites that contain this type of material as reinforcement should also show this same type of behavior. In the case of tungsten fibers, the situation is different. Although considerable scatter in strain at failure is encountered, the accompanying scatter in stress is small provided that a certain amount of plastic deformation has occurred. This behavior is shown schematically in figure 15(b). An increase from 1.4- to 2.8-percent strain at failure amounts to about a 5-percent scatter in tensile strength. The uniformity of metallic fibers should cause the composites made with them to exhibit much more uniform properties.

Fiber orientation. - Although the composites described in this paper contained continuous and discontinuous fibers oriented in a direction parallel to the tensile axis, the effect of fiber orientation on the properties of composites should be mentioned. Two fiber orientations will be considered: random and uniaxial.

From the standpoint of fabrication, it is possible to get much higher fiber contents by using uniaxial orientation. Random orientations usually have lower fiber contents because of arching or "tenting" at the fiber intersections.

From the standpoint of mechanical properties, the orientation of the fibers with respect to the tensile axis is a principal factor influencing the efficiency of reinforcement. This may be best illustrated by examining the "elastic" behavior of composites.

The "elastic" behavior of the composites observed in this investigation agrees quite well with the values predicted by equation (3). These data show that the modulus of elasticity of a composite is a linear function of fiber content. The fact that some investigators found a linear relation of modulus of elasticity with fiber content (ref. 7), while others did not (refs. 12 and 35), may be explained by the use of the mathematical analysis of the transverse, as well as the longitudinal, elastic properties of laminates presented in reference 36. The calculations in reference 36 are based on an epoxy matrix reinforced with music wire of square cross section. The equations developed for the longitudinal modulus E_L (parallel to the fiber axis) show that the modulus of a composite is a linear function of fiber content. The equations developed for the transverse modulus E_T (perpendicular to the fiber axis) did not yield such a linear relation. The traverse modulus is presented as a function of fiber geometry, Poisson's ratio, interfiber spacing, and volume percent fiber. As shown in figure 16, the longitudinal modulus varies linearly with fiber content, while the traverse modulus varies almost as a hyperbolic function. Although the equations developed for the transverse modulus of composites in the case of wires of a square cross section remains relatively simple, the calculations for reinforcement with circular fibers become complex. Calculations based upon fibers of a circular cross section yield a curve of the same shape, although displaced slightly. The experimental data presented in reference 36 for music wire reinforced epoxy laminates showed good agreement with the calculations presented.

The tungsten-fiber-reinforced copper composites tested in our investigation and those reported in reference 7 were composed of longitudinally oriented fibers and were tested in the direction parallel to the reinforcement. No component of the traverse modulus would be expected; therefore, the modulus should follow the relation predicted for the longitudinal modulus. The composites reported in reference 12 were composed of randomly oriented, kinked fibers, and the modulus measured could be considered to be a summation of the components of E_T and E_L of each fiber depending upon its orientation. The data should fall between the E_L and the E_T values. Since composites were tested with fiber contents ranging from 0 to 50 volume percent fiber, these values should fall on a line parallel to the E_T values, but on the lower leg of the hyperbola and should approximate linear behavior. In fact, this is what appears to have occurred; however, E_T data are not available on this system to make an exact evaluation. A similar analysis may be applied to the data reported in reference 35, except that there was less deviation from longitudinal orientation and the modulus values were closer to the anticipated E_L.

The effect of orientation on the plastic properties of a composite may be illustrated by the data of reference 12 on composites of matrices of copper or silver reinforced with tungsten, molybdenum, or steel fibers (ref. 12). In one series of composites, a copper matrix was reinforced with randomly oriented, kinked tungsten fibers of 5-mil diameter. The tensile results obtained for these composites was considerably below the results obtained in the investigation at Lewis where unidirectional reinforcement was used. In reference 12, a composite containing 30 volume percent fiber, randomly oriented, exhibited a tensile strength of 35,000 psi, while in the investigation at Lewis, a composite containing 28 volume percent fiber, uniaxially oriented, was found to have an ultimate tensile strength of 97,500 psi (fig. 3(b)). Since there was probably little difference in the materials used and temperatures encountered during fabrication, the differences were probably due to the effect of orientation.

From this it would appear that the chosen orientation of reinforcing fibers should be dictated by the application involved. If isotropic properties are desired, then random orientation should be used. This would tend to give more or less uniform properties in any direction; however, this is done at the sacrifice of the maximum strengthening potential in any one direction. If the loading is such that the load is applied in only one direction, the maximum strengthening potential of the fiber-reinforced composite could be realized by orienting the fibers in a direction parallel to the direction of loading.

CONCLUSIONS

This investigation of tungsten-fiber-reinforced copper composites was conducted to determine the stress-strain behavior and tensile properties of metallic composites and to relate them to the properties of the base materials. Room-temperature tensile and dynamic modulus tests were used to determine these properties. The following conclusions may be drawn:

1. Stress-strain behavior of composites of this type show that all stages of deformation may be represented by the following general equation:

$$\sigma_c^* = \sigma_f^* A_f + \sigma_m^* A_m$$

2. Four stages of deformation were observed.

(a) Stage I - Upon initial loading, the deformation of the matrix and the fiber is elastic; the composite deforms elastically. Behavior in the initial elastic region may be expressed by a form of the general equation

$$E_c = E_f A_f + E_m A_m$$

(b) Stage II - With increasing stress, the matrix deforms plastically, while the fiber remains elastic; the composite exhibits secondary "elastic" behavior. Behavior in the secondary elastic region may be expressed by a form of the general equation

$$E_c' = E_f A_f + \frac{\sigma_m^*}{\epsilon} A_m$$

(c) Stage III - With increasing stress, the deformation of the fiber also becomes plastic; the composite deforms plastically. Behavior in the plastic region may be expressed by the general equation.

(d) Stage IV - The fourth stage represents deformation in which the fibers fail at random points of weakness and an accumulation of random failures results in failure of the composite.

3. The ultimate tensile strength of the composites is proportional to the fiber content and the properties of the components as shown by the equation

$$\sigma_c = \sigma_f A_f + \sigma_m^* A_m$$

4. Elongation of the composite, at failure, decreased with increasing fiber content. The composite showed greater elongation than the fibers that had been tested individually.

5. Composites reinforced with discontinuous fibers were fully as efficient as those reinforced with continuous fibers and were found to utilize the full strength of the fibers. The discontinuous-fiber-reinforced composites displayed the same behavior as that predicted by the equations and found to hold for continuous-fiber-reinforced composites.

CONCLUDING REMARKS

As a result of the analyses of the experimental data obtained in this investigation and a comparison to other composite systems, it is felt that, although some of the concepts developed for these different systems are similar, there are many situations that do not permit the generalization of these concepts from one system to another. In some cases similarities do exist, and equations representing the behavior of widely dissimilar types of composites may be the same; however, other factors, unique to a particular system, may cause large differences in results. For example, in glass-reinforced plastics, bonding difficulties and premature failure due to defects are encountered. These give rise to very high critical aspect ratios. In tungsten-fiber-reinforced copper composites, these problems are not nearly as serious, resulting in much lower critical aspect ratios for reinforcement. It is expected that other metallic composites may show similar trends.

Composites reinforced with metallic fibers have strength values that were much more uniform and reproducible than those reported for glass-reinforced plastics. This was due to the relative uniformity of the properties of the metallic fibers as opposed to the scatter in strength encountered in glass fibers or in whiskers.

In addition, the orientation of the fibers with respect to the tensile axis would be a principal factor influencing the efficiency of reinforcement. While uniaxial orientation maximizes the properties in one direction, random orientation tends to give the composite more uniform properties in all directions, but at the sacrifice of properties in a single direction.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, June 4, 1963

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TABLE I. - TENSILE STRENGTHS OF TUNGSTEN-FIBER-REINFORCED COPPER COMPOSITES

(a) Continuous reinforcement

Specimen number	Volume percent fiber, v/o	Volume-percent-fiber calculation method	Grip type	Diameter, in.	Area calculation method	Test method	Number of wires	Tensile strength, psi
Fiber diameter, 3 mils								
3-01	11.9	(a)	(b)	0.122	(c)	(d)	197	53.0×10^3
3-02	24.1			.116			361	102.8
3-03	38.1			.118			588	141.3
3-04	46.5			.122			768	168.6
3-05	49.8			.118			773	177.8
3-06	52.9			.114			763	184.9
3-07	73.2			.040	(e)	(f)	130	240.8
Fiber diameter, 5 mils								
5-01	12.6	(a)	(b)	0.097	(e)	(f)	48	47.7×10^3
5-02	15.8			.089			50	52.0
5-03	16.1			.125			100	63.5
5-04	27.2			.096			100	98.3
5-05	27.2			.096			100	100.1
5-06	28.0	(g)		.191	(c)	(d)	---	97.5
5-07	33.6	(a)		.122	(c)	(f)	177	102.2
5-08	33.9		(h)	.113	(c)	(d)	$172\frac{1}{4}$	122.4
5-09	40.2		(b)	.093	(e)	(f)	139	137.0
5-10	47.7		(b)	.117	(c)	(d)	261	154.5
5-11	52.7		(h)	.113	(c)	(d)	267	189.6
5-12	53.6		(b)	.123	(c)	(d)	325	182.2
5-13	54.4			.095	(e)	(f)	197	188.4
5-14	57.2			.118	(c)	(d)	317	178.8
5-15	57.3			.121	(c)	(d)	338	189.7
5-16	62.4			.124	(c)	(d)	372	210.9
5-17	62.7			.077	(e)	(f)	150	215.1
5-18	63.5			.121	(c)	(d)	369	213.9
5-19	65.0		(h)	.112	(c)	(d)	$325\frac{1}{4}$	225.7
5-20	67.1		(b)	.122	(e)	(f)	400	231.0
5-21	67.4			.119	(c)	(d)	385	228.3
5-22	68.1			.117	(c)		371	227.7
5-23	69.2			.108	(e)		323	235.6
5-24	70.2			.108	(e)		326	238.0
5-25	70.2			.085	(e)	(f)	204	238.4
5-26	71.6			.118	(c)	(d)	399	242.9
5-27	72.4			.083	(e)	(f)	200	238.9
5-28	72.9			.110	(c)	(d)	356	239.9
5-29	75.4			.127	(e)	(f)	483	249.8
5-30	76.8			.087	(e)	(f)	231	254.9
Fiber diameter, 7 mils								
7-01	26.9	(a)	(b)	0.122	(c)	(d)	82	85.6×10^3
7-02	32.1		(b)	.124			100	94.1
7-03	33.7		(h)	.114			$88\frac{3}{4}$	104.2
7-04	34.6		(b)	.121			149	103.5
7-05	49.4		(b)	.122			100	163.2
7-06	50.5		(b)	.112	(e)		129	175.0
7-07	58.9		(h)	.102	(c)		$124\frac{1}{2}$	184.7
7-08	59.5		(b)	.111	(e)		150	172.4
7-09	63.3		(h)	.113	(c)		$164\frac{3}{4}$	197.5
7-10	64.6		(b)	.123			196	213.5
7-11	72.6			.116			199	236.7
7-12	73.1			.104			160	201.4
7-13	78.7			.0306	(e)	(f)	15	227.5
7-14	80.0			.0375			23	225.1
7-15	80.6			.0374			23	255.4
7-16	83.9			.0366			23	227.5
7-17	84.5			.0365			23	260.3
7-18	86.3			.0361			23	246.8
7-19	87.1			.0360			23	255.4
7-20	87.6			.0198			8	260.1

[a]Volume percent fiber calculated by counting wires from photograph.

[b]Rods brazed into grips to form tensile specimens.

[c]Area calculated from micrometer measurements of diameter.

[d]Strain recorded from extensometer.

[e]Area calculated from planimeter measurements of photographs.

[f]Strain recorded from crosshead movement.

[g]Volume percent fiber calculated by specific gravity or density measurements.

[h]Rods ground into tensile specimens.

TABLE I. - Concluded. TENSILE STRENGTHS OF TUNGSTEN-FIBER-REINFORCED COPPER COMPOSITES

(b) Discontinuous reinforcement

Specimen number	Volume percent fiber, v/o	Volume-percent-fiber calculation method	Grip type	Diameter, in.	Area calculation method	Test method	Number of wires	Tensile strength, psi
Fiber diameter, 5 mils								
5D-01	12.4	(a)	(b)	0.143	(c)	(d)	101	41.1×10^3
5D-02	14.1			.143			117	57.3
5D-03	14.4			.135			105	56.6
5D-04	18.2			.126			115	62.6
5D-05	21.3			.125			133	49.0
5D-06	23.3			.129			154	57.7
5D-07	25.2			.111		(e)	124	91.1
5D-08	27.9			.120		(e)	161	115.8
5D-09	32.3			.101		(d)	132	110.0
5D-10	32.4			.117		(e)	178	100.3
5D-11	35.7			.101		(d)	146	120.0
5D-12	36.0			.128		(d)	234	90.3
5D-13	37.7			.118		(d)	210	93.5

[a]Volume percent fiber calculated by counting wires from photograph.

[b]Rods brazed into grips to form tensile specimens.

[c]Area calculated from micrometer measurements of diameter.

[d]Strain recorded from crosshead movement.

[e]Strain recorded from extensometer.

TABLE II. - MODULUS OF ELASTICITY OF

TUNGSTEN-FIBER-REINFORCED

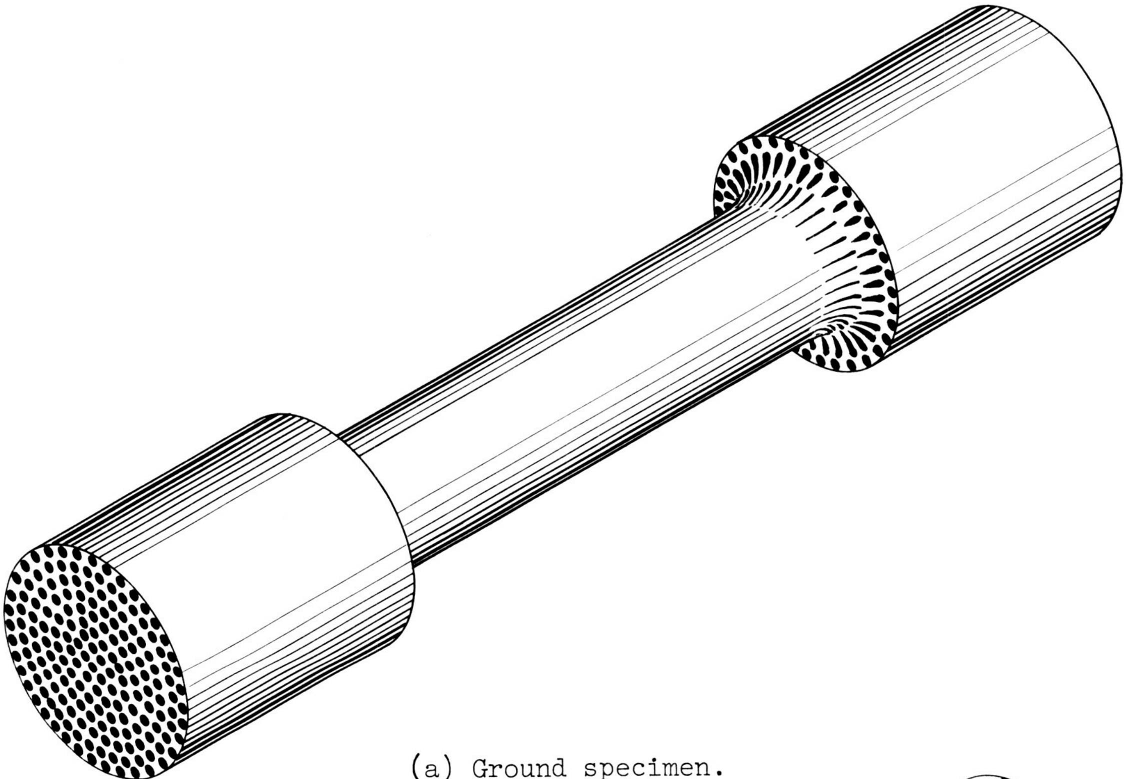
COPPER COMPOSITES

(a) Continuous reinforcement

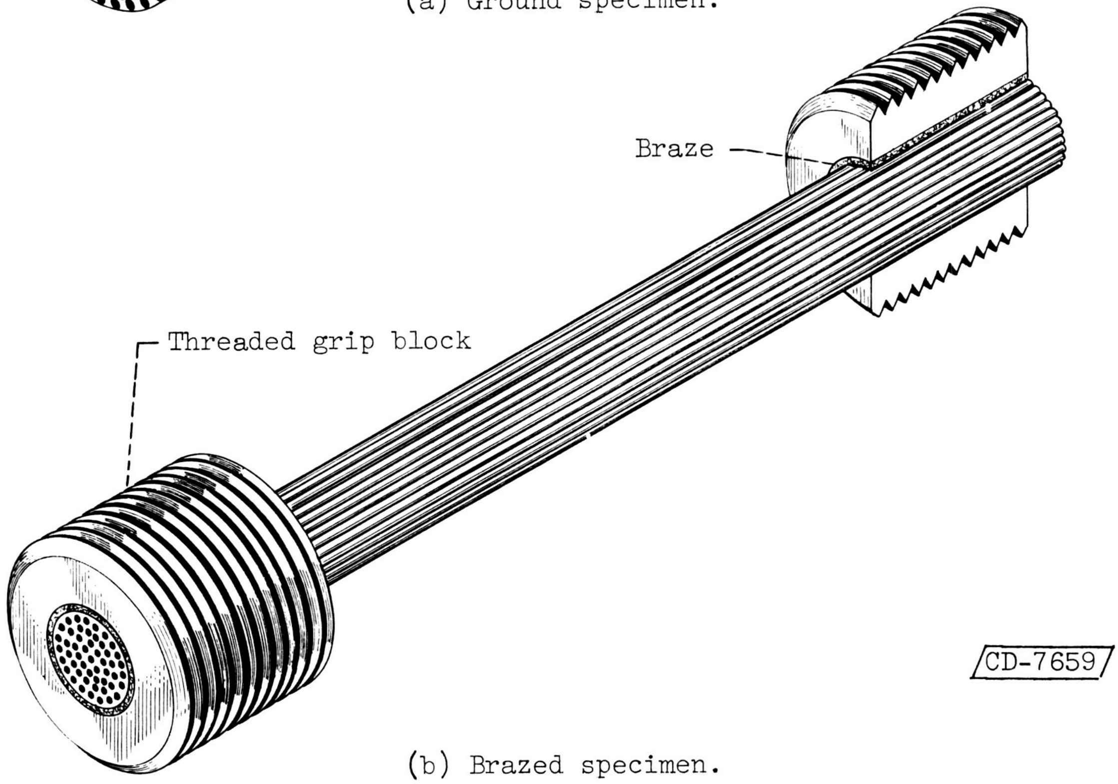
Specimen number	Volume percent fiber, v/o	Modulus of elasticity, psi
E-01	18.7	26.4×10^{6}
E-02	24.3	26.7
E-03	26.7	28.3
E-04	29.0	30.0
E-05	32.3	29.8
E-06	35.9	30.2
E-07	55.0	41.6
E-08	57.6	41.7
E-09	64.9	44.4
E-10	66.6	44.3
E-11	67.3	45.6
E-12	75.5	48.3
E-13	Copper	17.7
E-14	Tungsten	58.8

(b) Discontinuous reinforcement

ED-01	23.0	26.1×10^{6}
ED-02	25.0	28.9
ED-03	25.7	28.2
ED-04	26.9	27.9



(a) Ground specimen.



(b) Brazed specimen.

Figure 1. - Sketch of ground tensile specimen and brazed tensile specimen showing relation of reinforcing fiber to specimen configuration.

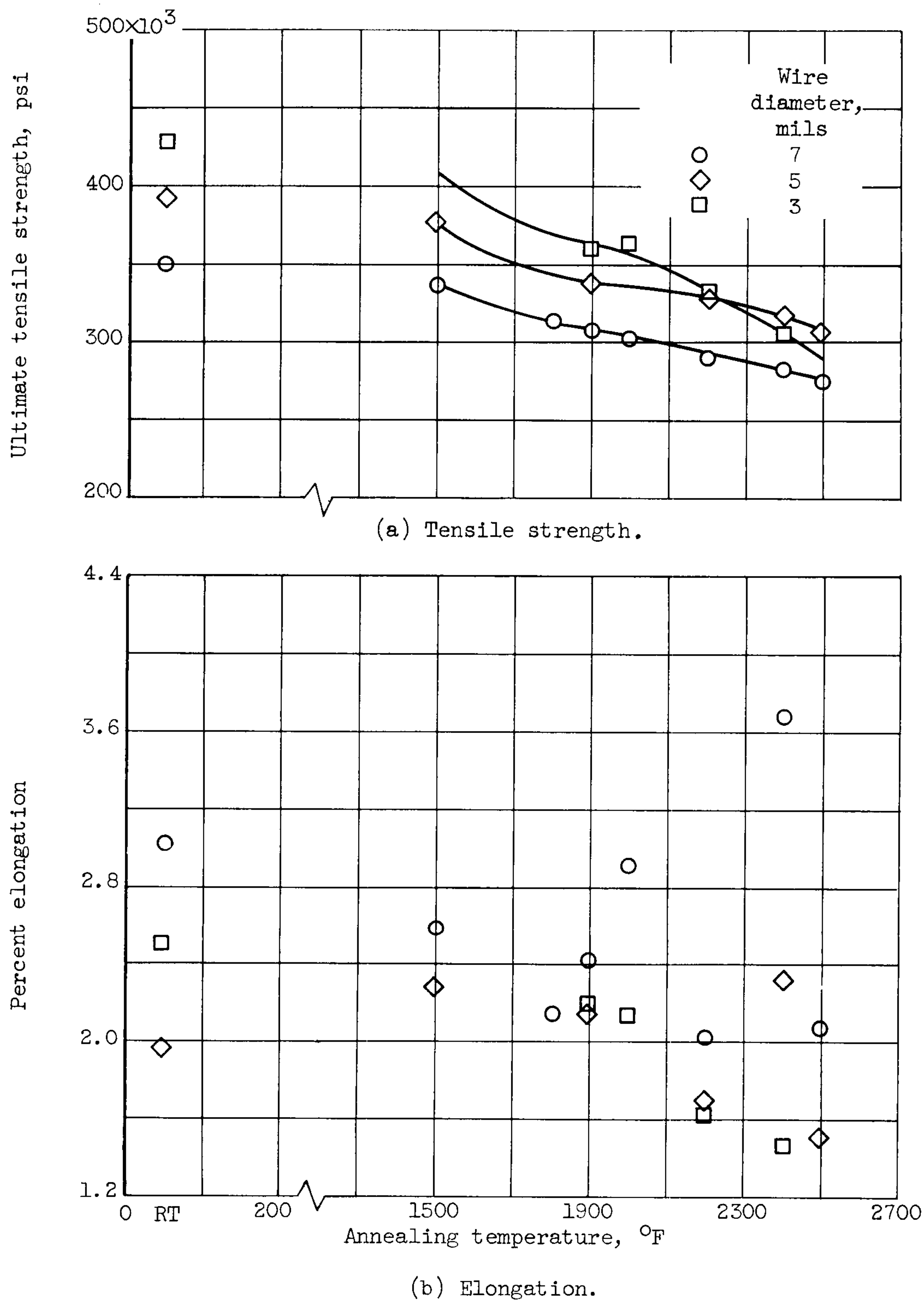
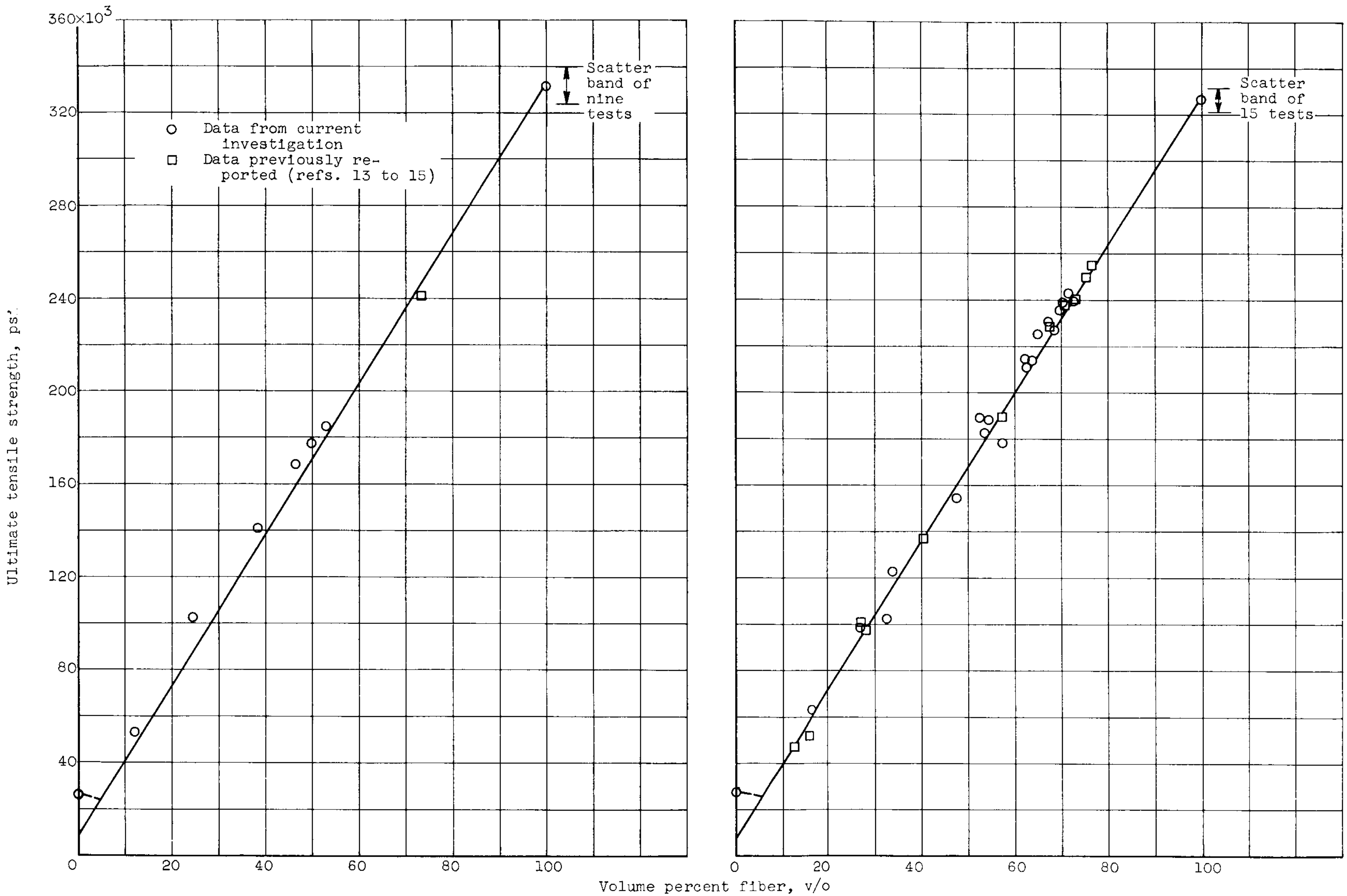


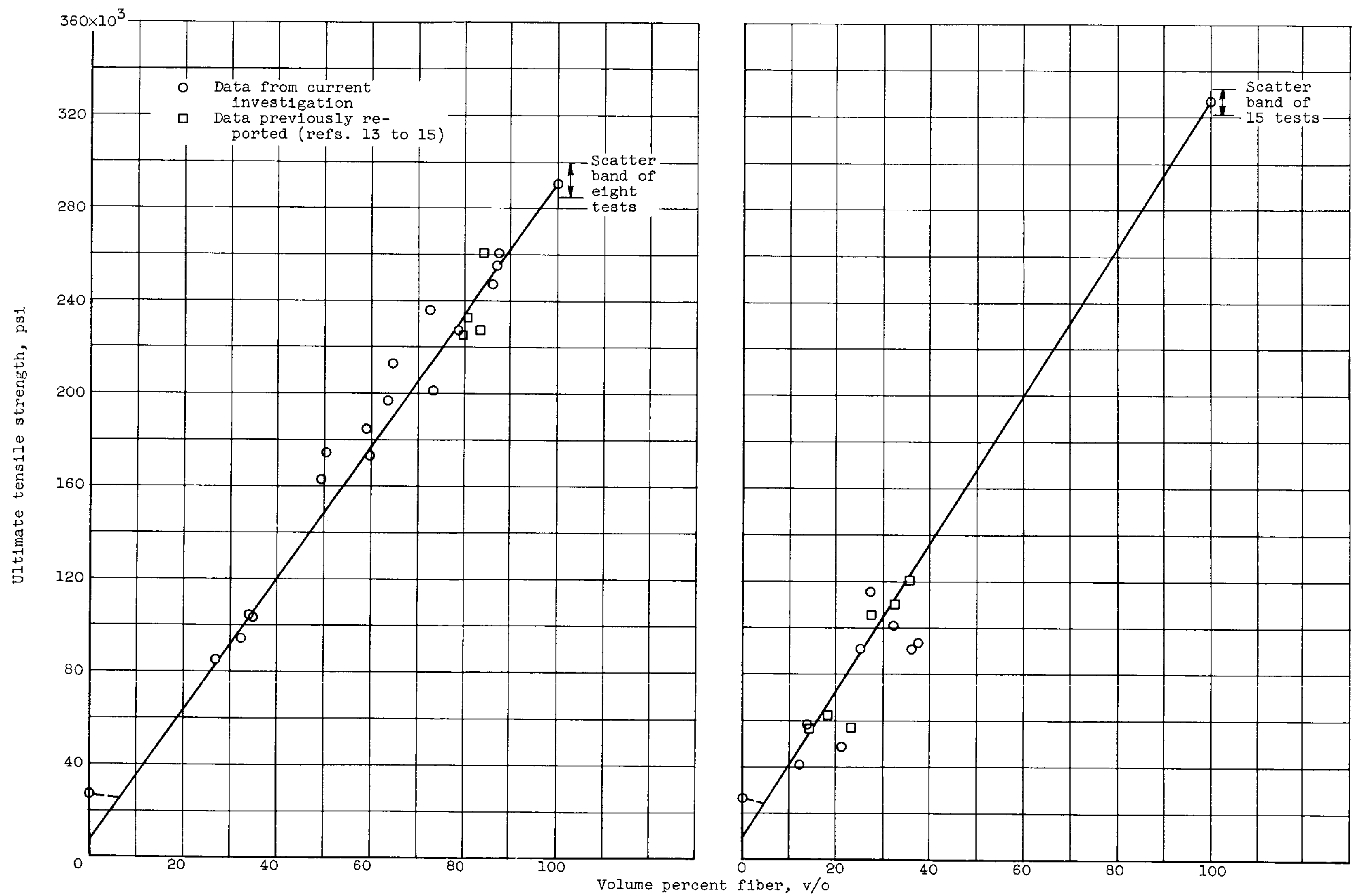
Figure 2. - Effect of annealing temperature on tensile strength and elongation of tungsten wires (annealed for 1 hr in vacuum).



(a) Continuous reinforcement with 3-mil-diameter tungsten fibers.

(b) Continuous reinforcement with 5-mil-diameter tungsten fibers.

Figure 3. - Tensile strengths of tungsten-fiber-reinforced copper composites.



(c) Continuous reinforcement with 7-mil-diameter tungsten fibers. (d) Discontinuous reinforcement with 5-mil-diameter tungsten fibers.

Figure 3. - Concluded. Tensile strengths of tungsten-fiber-reinforced copper composites.

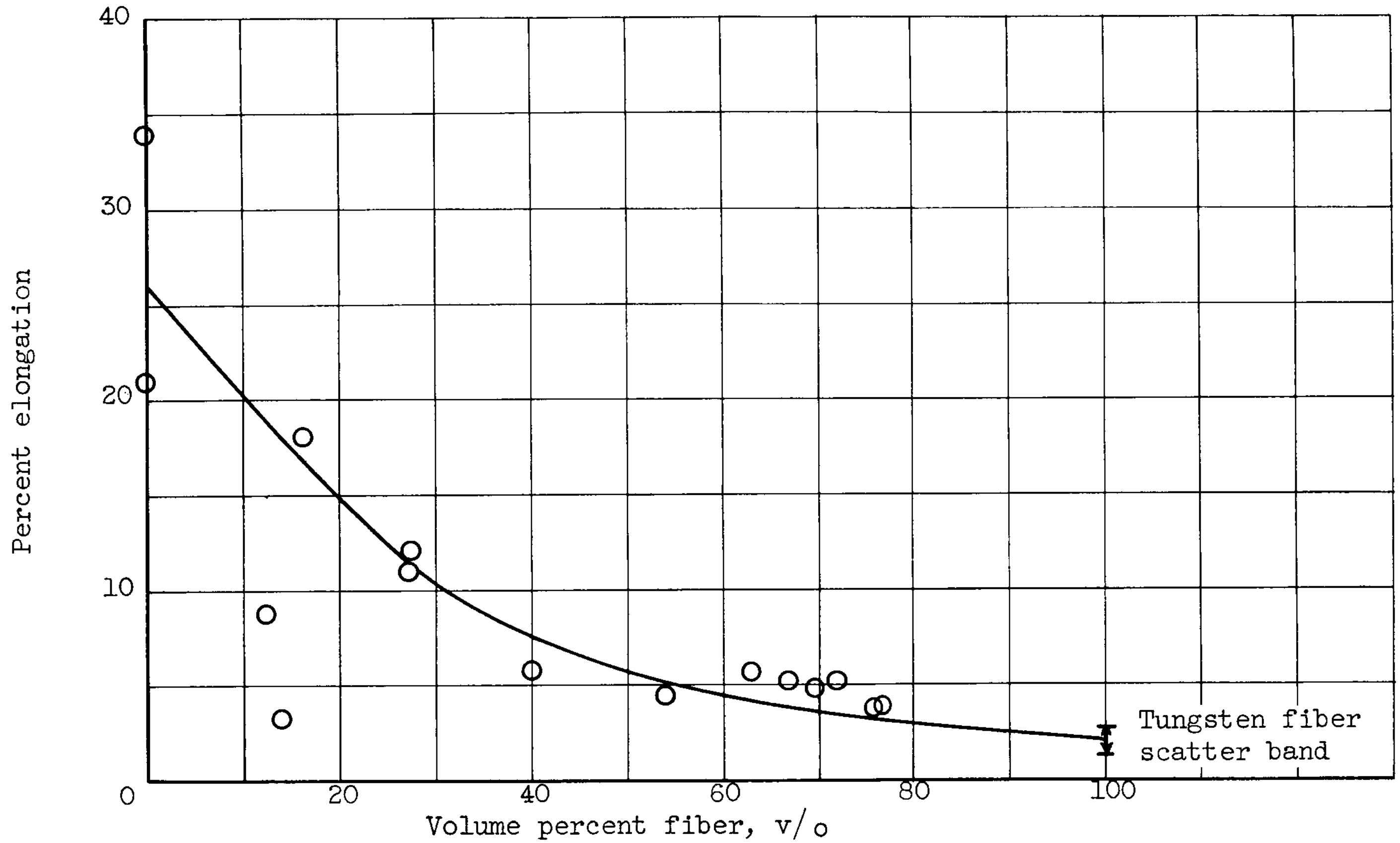
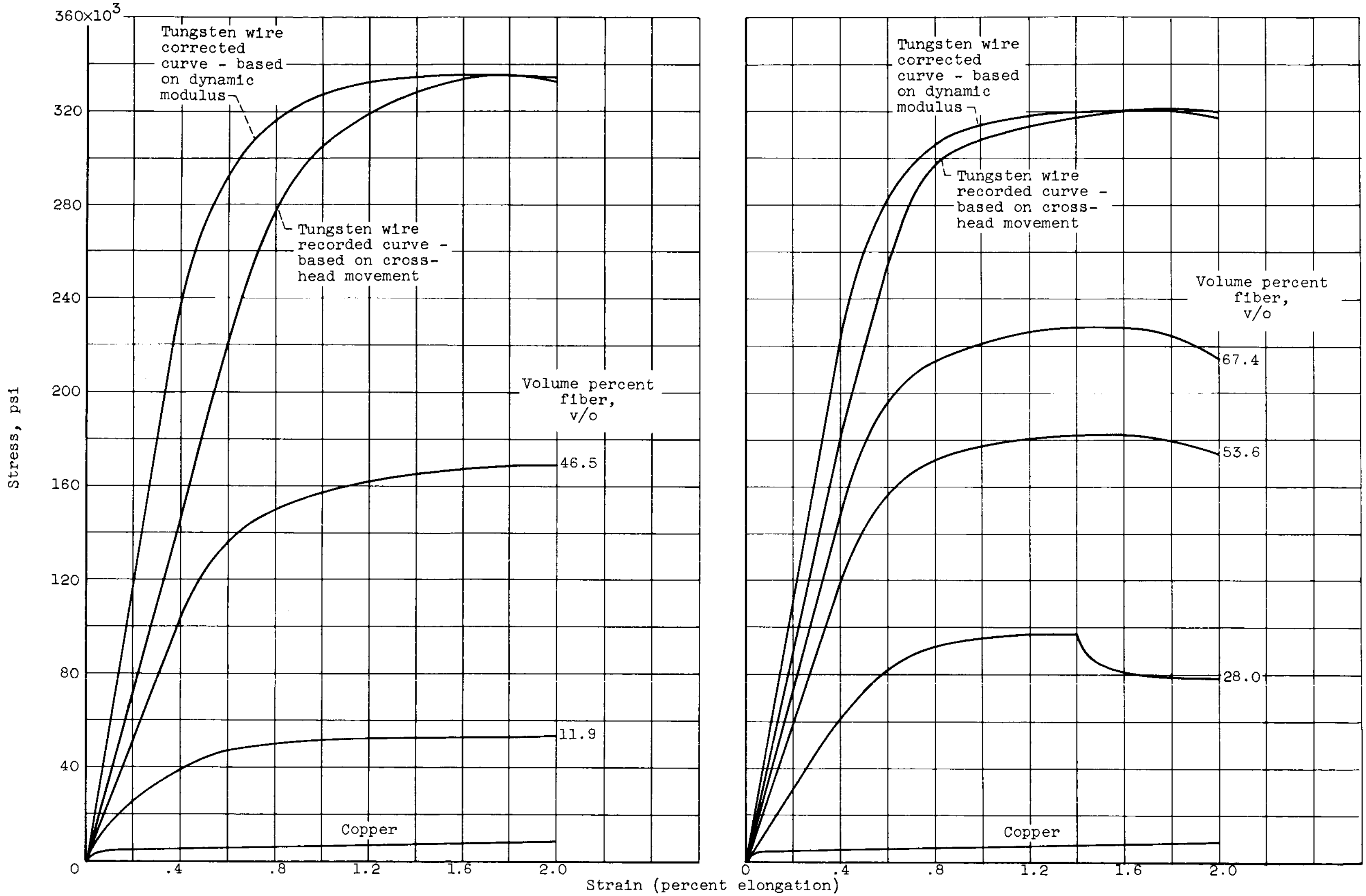


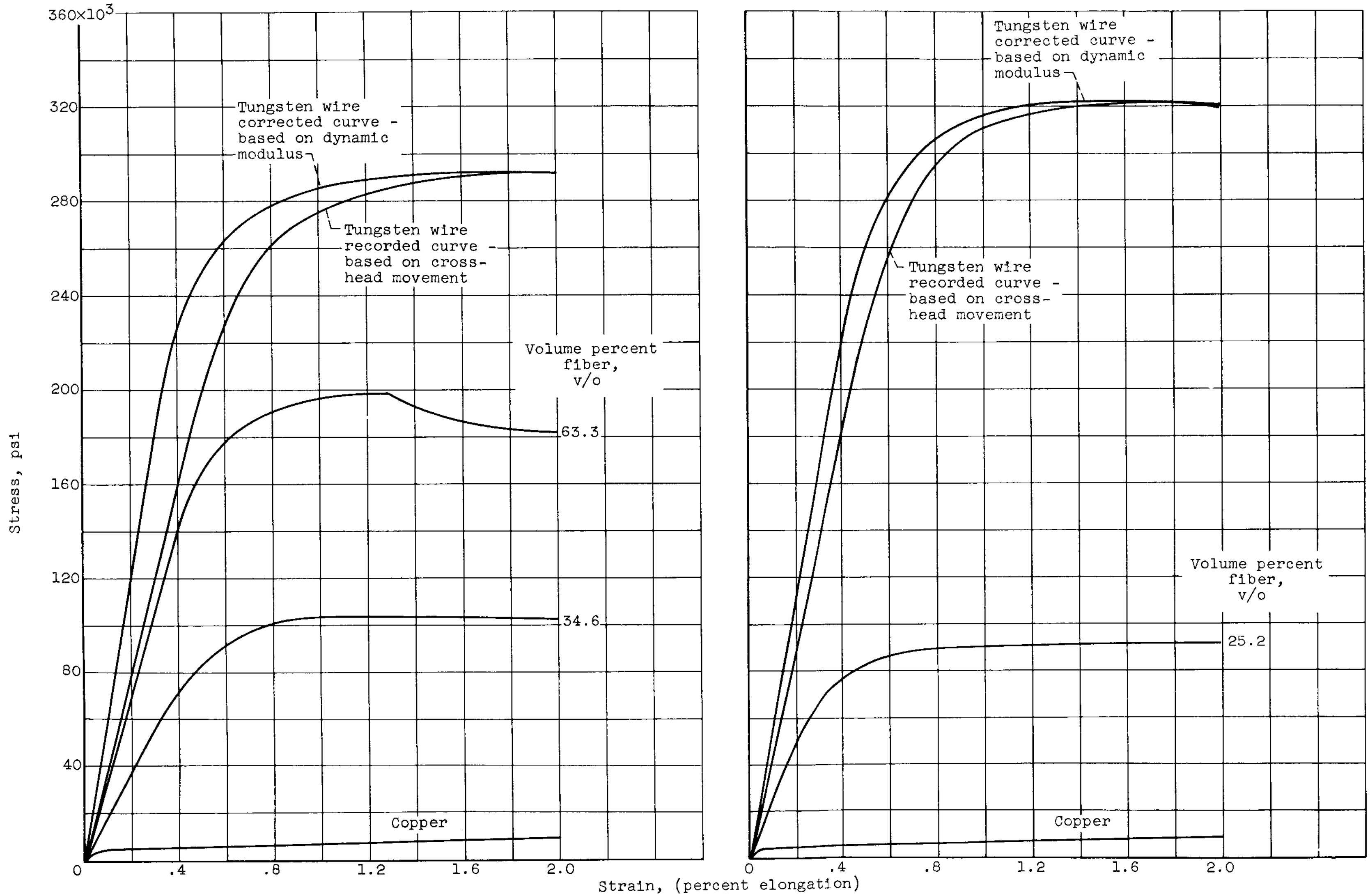
Figure 4. - Elongation at failure of composites reinforced with continuous 5-mil-diameter tungsten fibers.



(a) For 3-mil-diameter continuous tungsten reinforcement.

(b) For 5-mil-diameter continuous tungsten reinforcement.

Figure 5. - Stress-strain curves for tungsten wire, copper, and composites reinforced with tungsten wire.



(c) For 7-mil-diameter continuous tungsten reinforcement. (d) For 5-mil-diameter discontinuous tungsten reinforcement.

Figure 5. - Concluded. Stress-strain curves tungsten wire, copper, and composites reinforced with tungsten wire.

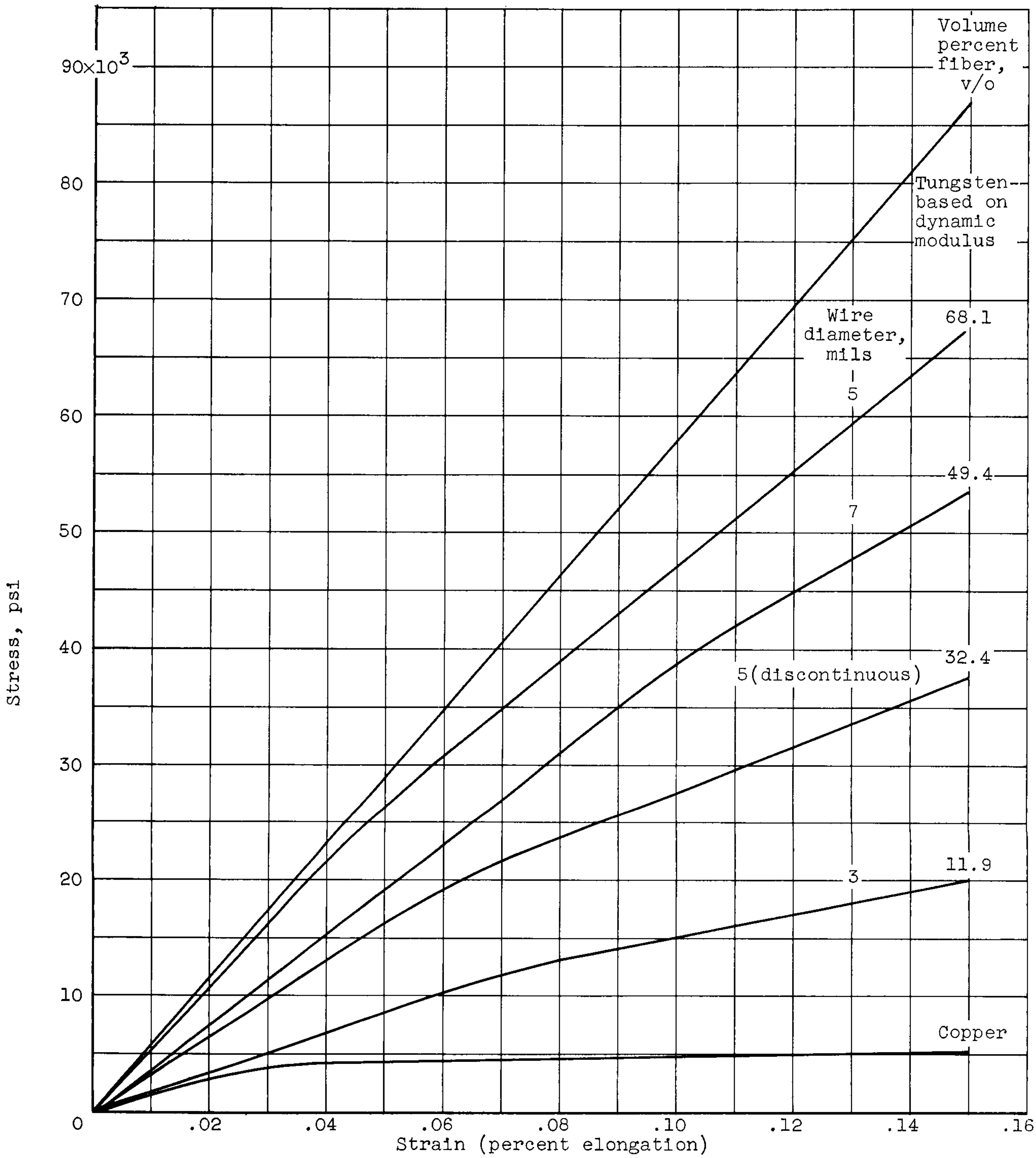


Figure 6. - Enlargement of low-strain region of stress-strain curves of tungsten, copper, and composites reinforced with tungsten fibers.

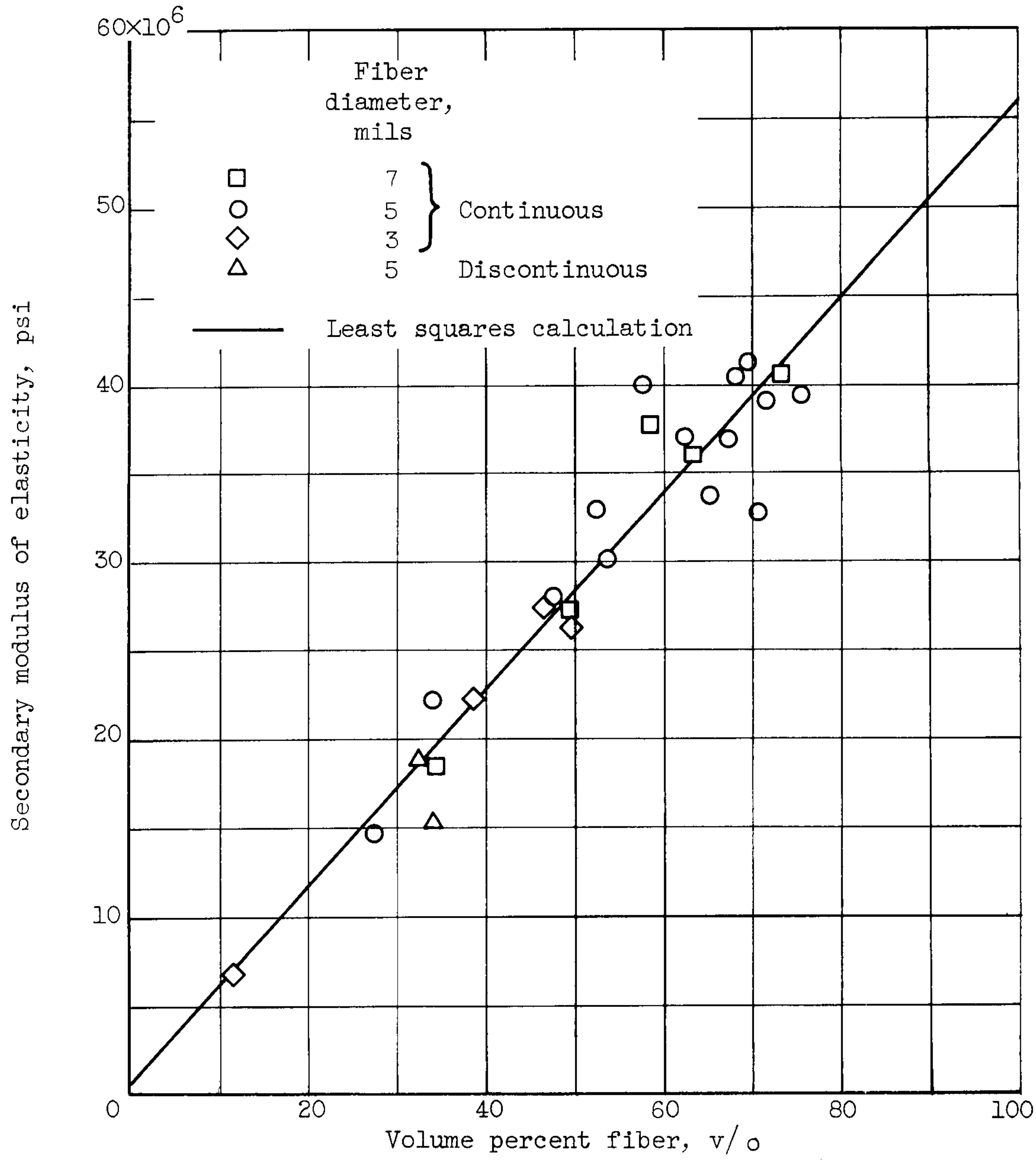


Figure 7. - Secondary modulus of elasticity for composites reinforced with tungsten fibers.

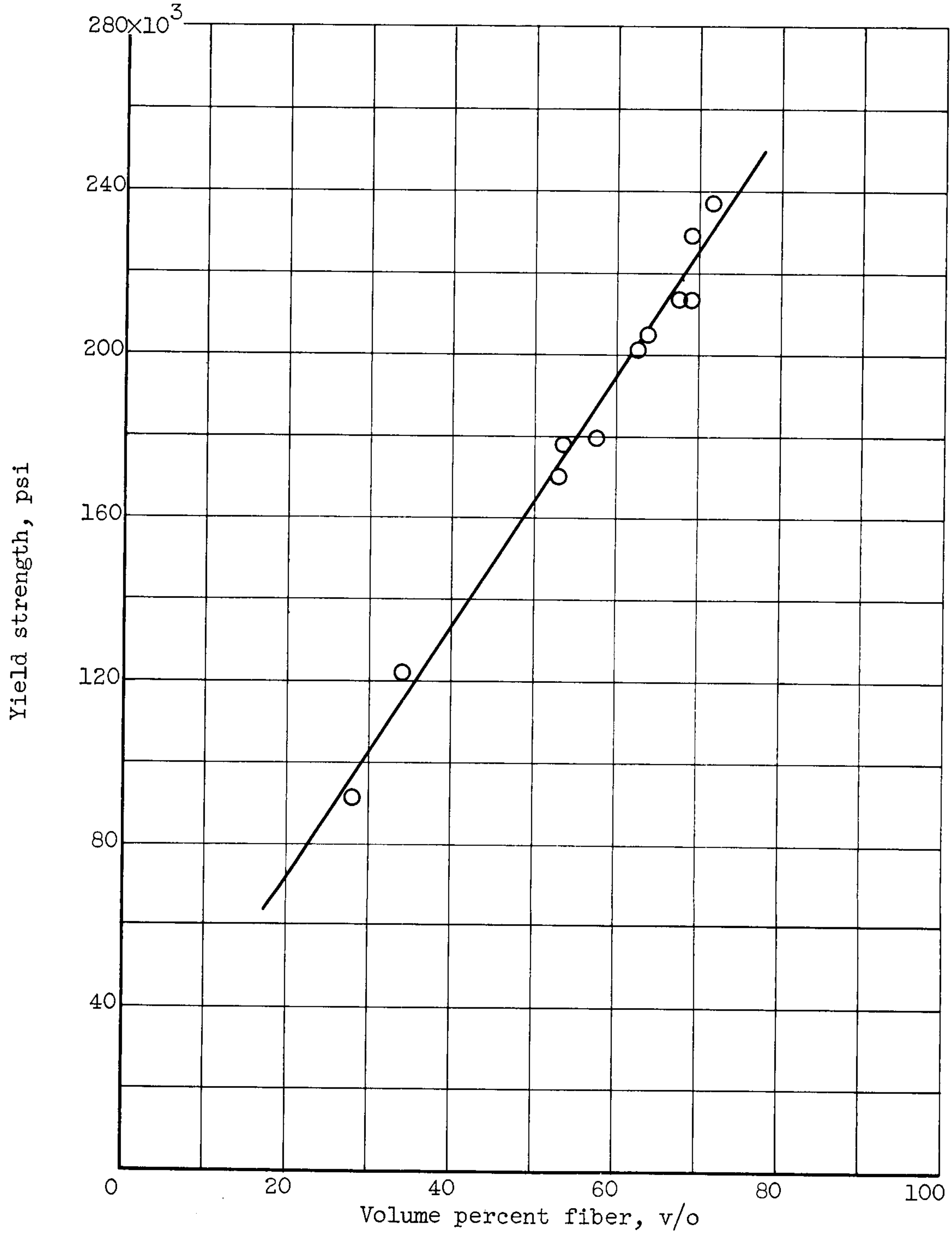


Figure 8. - Yield strength (based on secondary modulus) of composites reinforced with continuous 5-mil-diameter tungsten fibers.

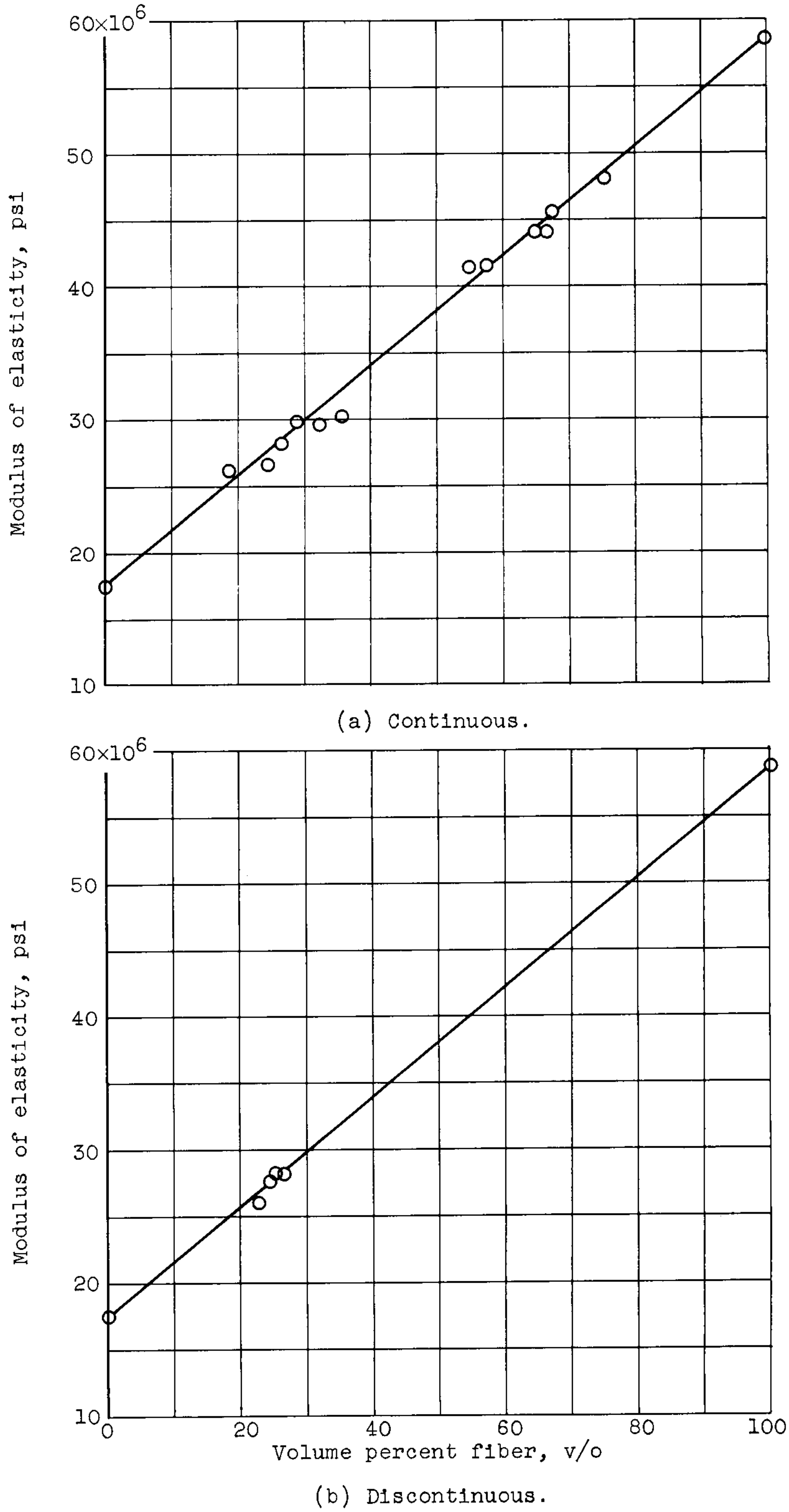


Figure 9. - Dynamic modulus of elasticity of tungsten, copper, and composites reinforced with continuous and discontinuous 5-mil-diameter tungsten fibers.

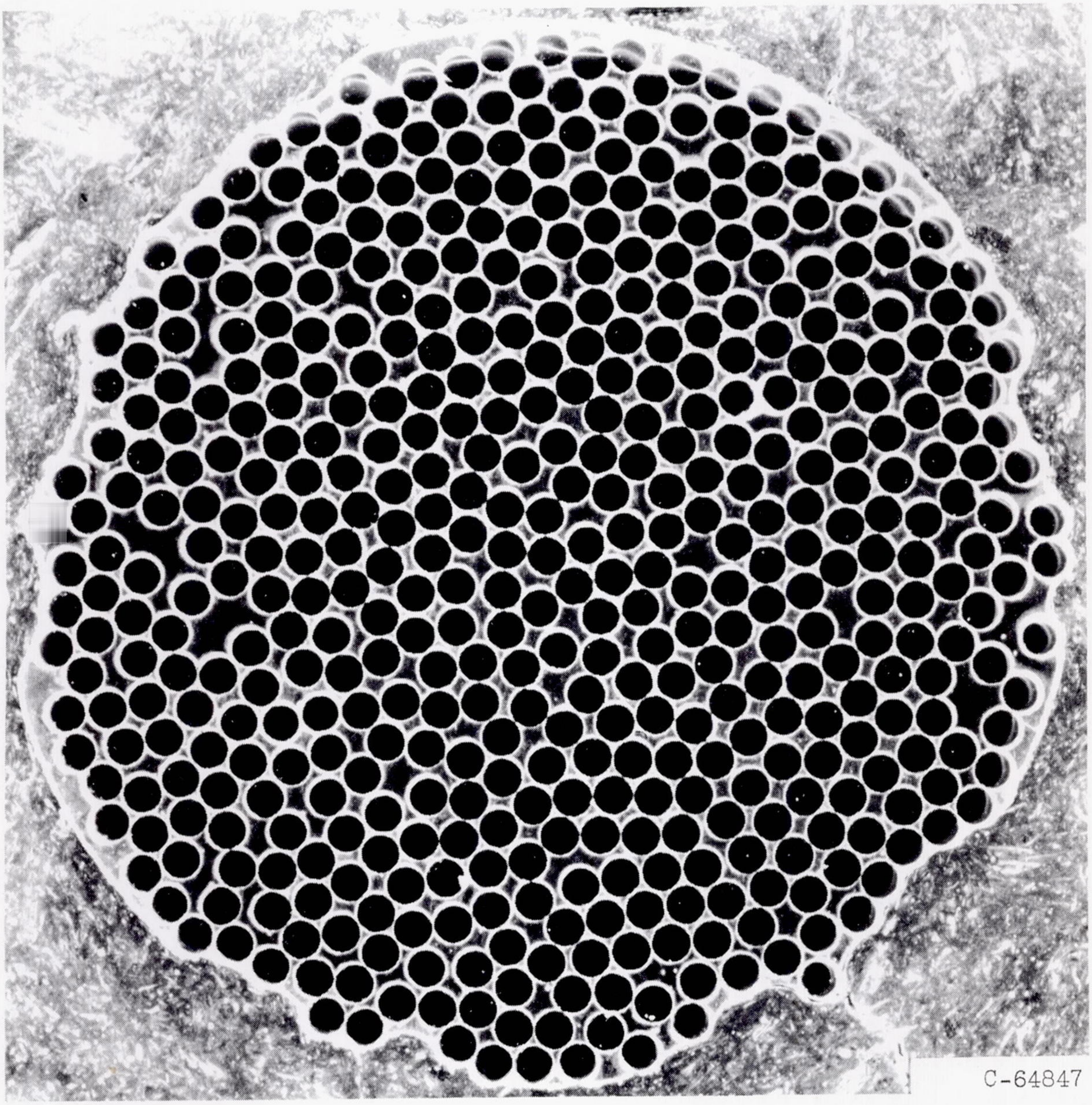


Figure 10. - Transverse section of continuous 5-mil-diameter tungsten-fiber-reinforced copper composite. Unetched; ×50.

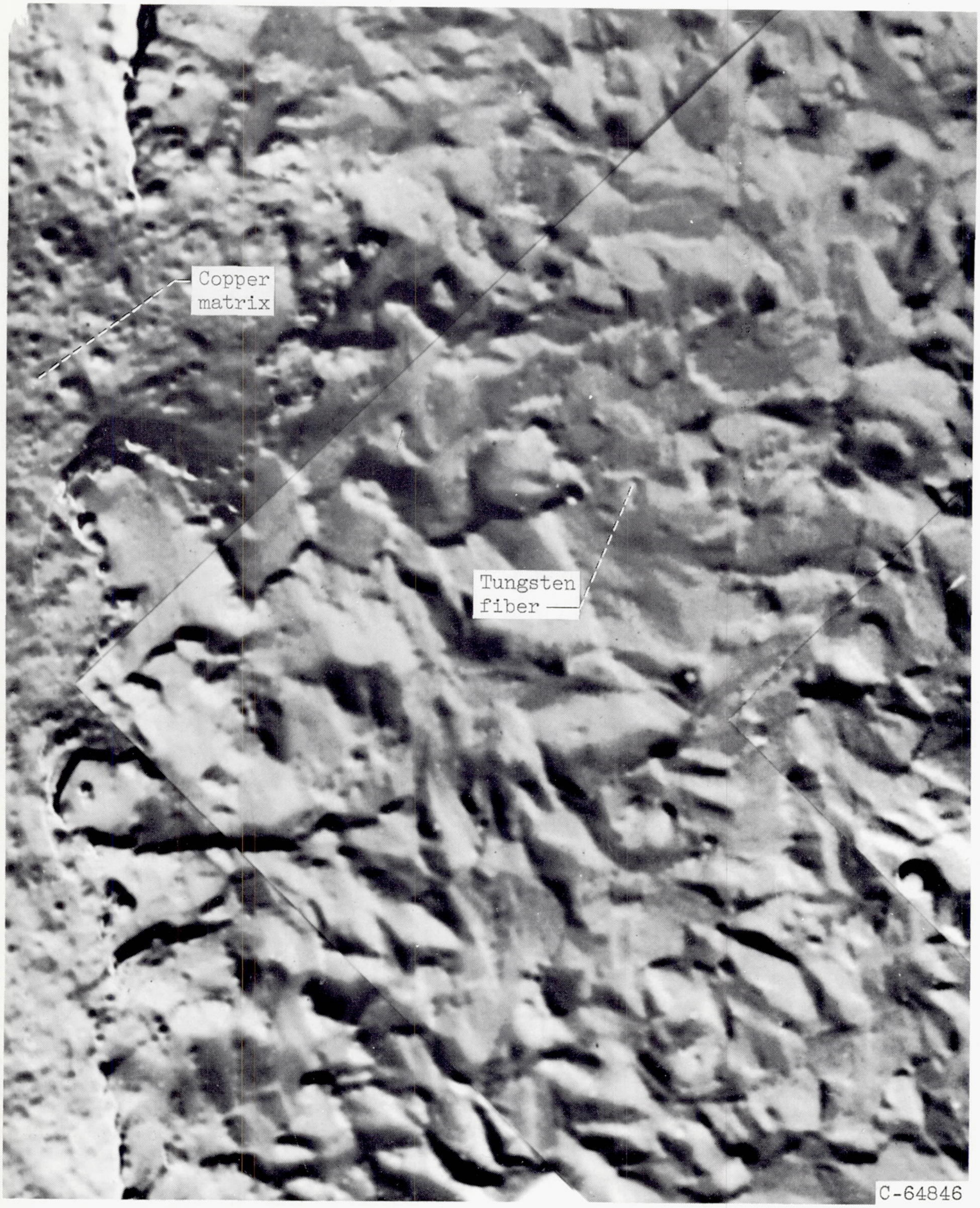


Figure 11. - Electron photomicrograph of transverse section of continuous 5-mil-diameter tungsten-fiber - copper-matrix interface. ×26,000.

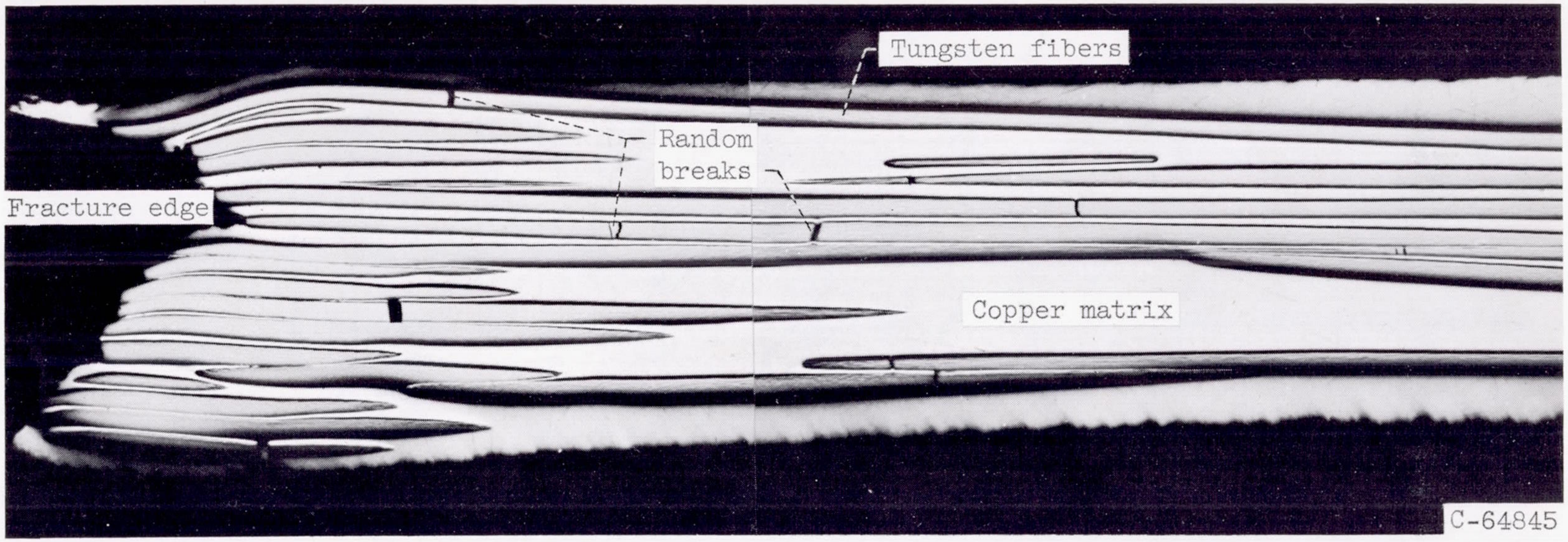


Figure 12. - Photomicrograph of the fracture edge of a composite reinforced with continuous 3-mil-diameter tungsten fibers. Unetched; ×50.

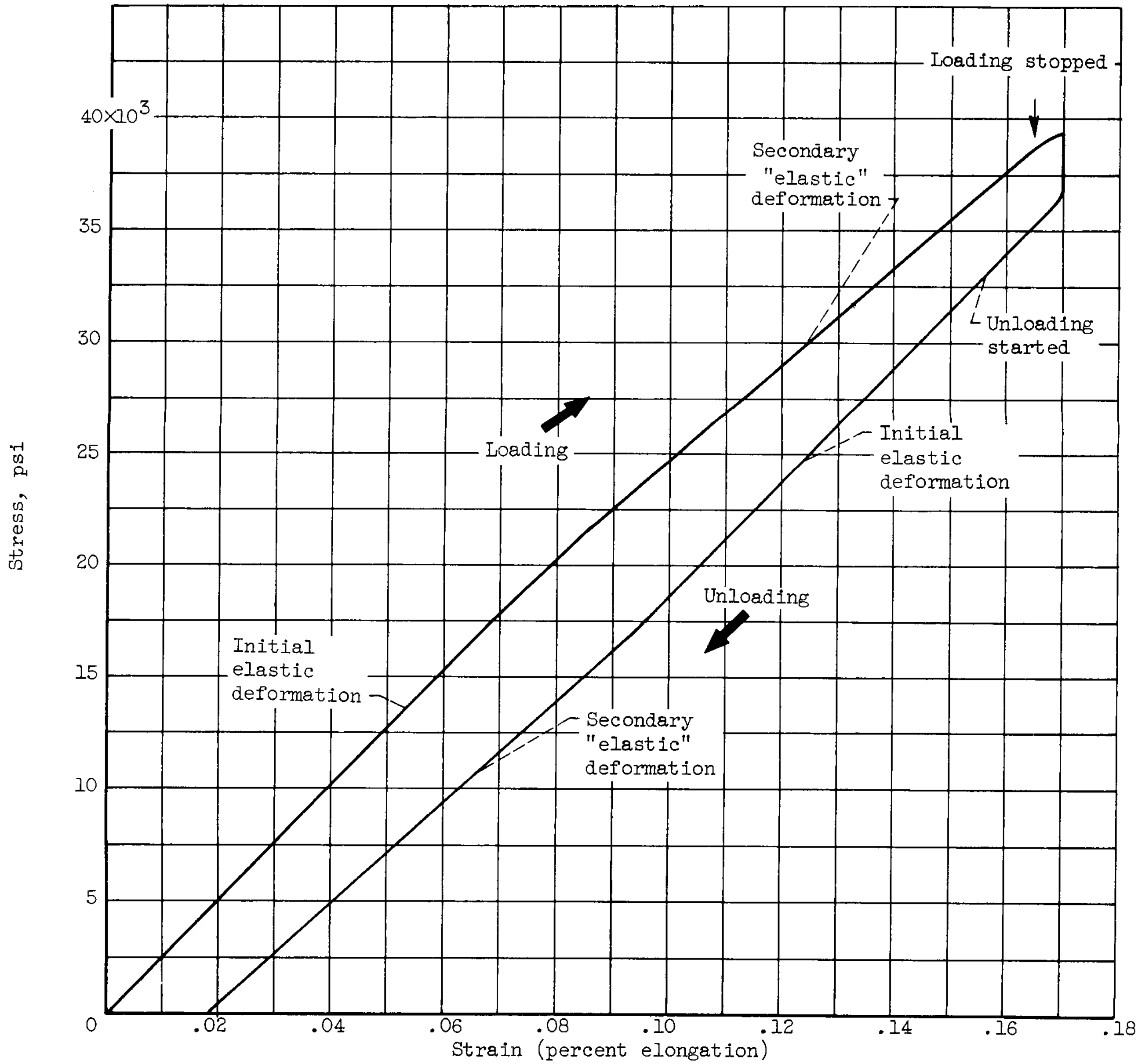


Figure 13. - Stress-strain curve for 5-mil-diameter tungsten-fiber-reinforced copper composite upon loading and unloading. Volume percent fiber, 18.7.

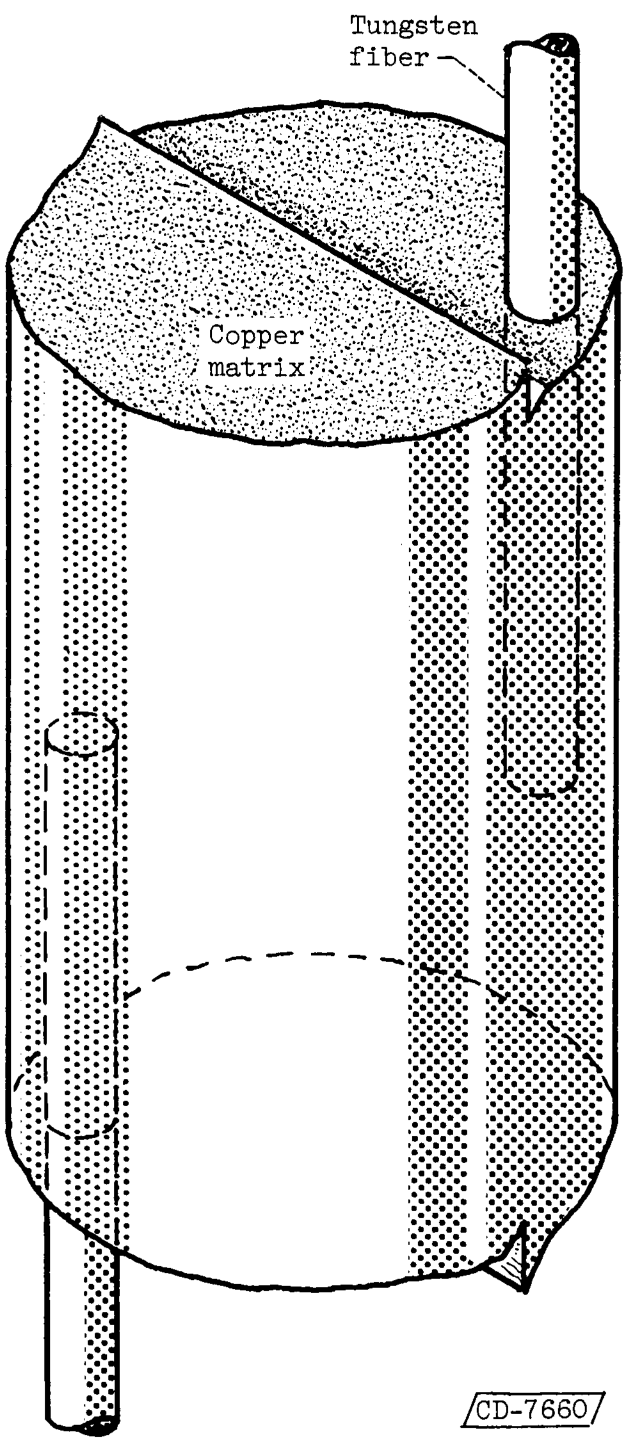
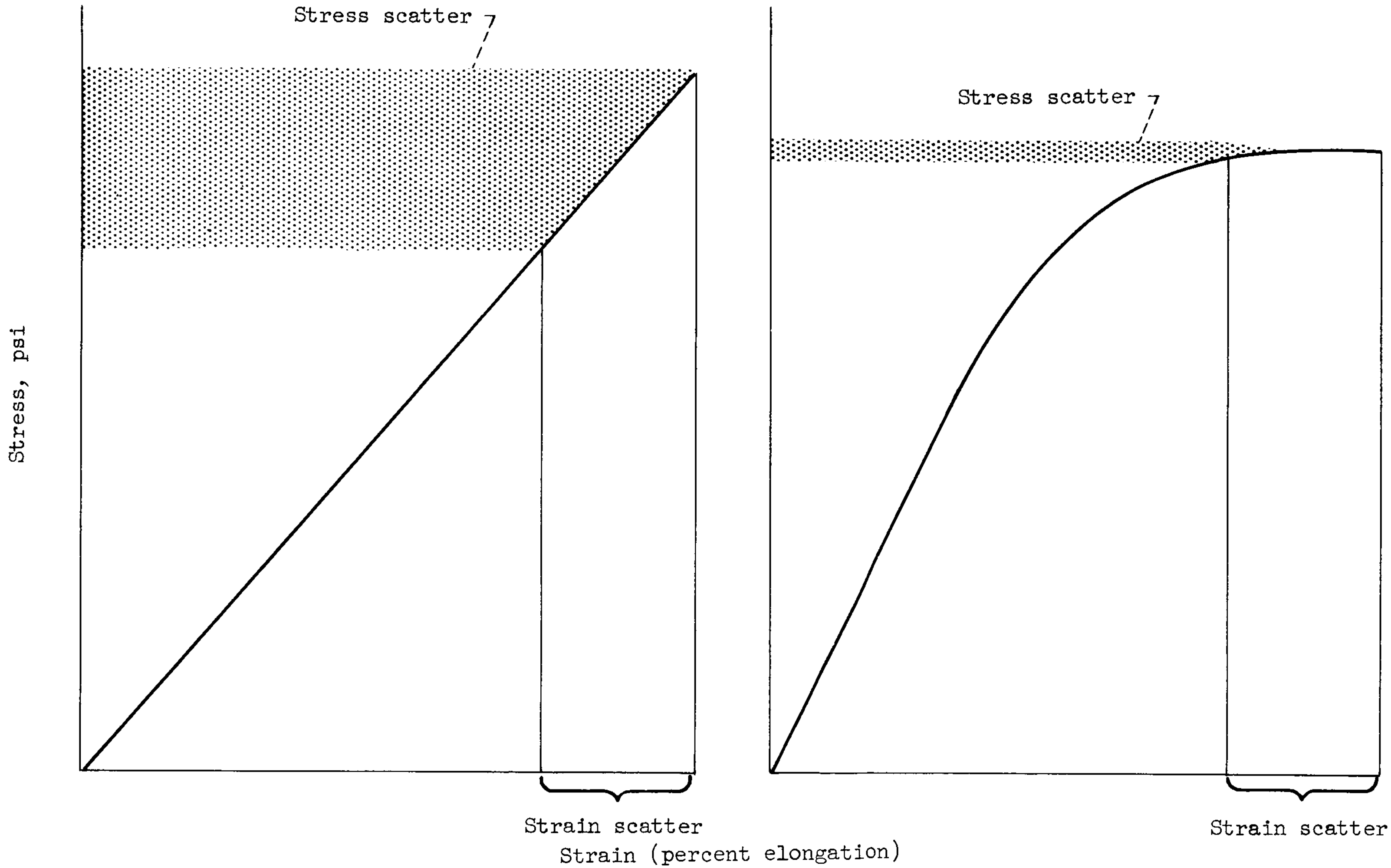


Figure 14. - Schematic loading diagram of a section of discontinuous-fiber-reinforced composite.



(a) Elastic material.

(b) Elastic plastic material.

Figure 15. - Schematic stress-strain curves comparing scatter of stress caused by equal scatter of strain for fibers exhibiting elastic deformation and fibers exhibiting elastic plastic deformation.

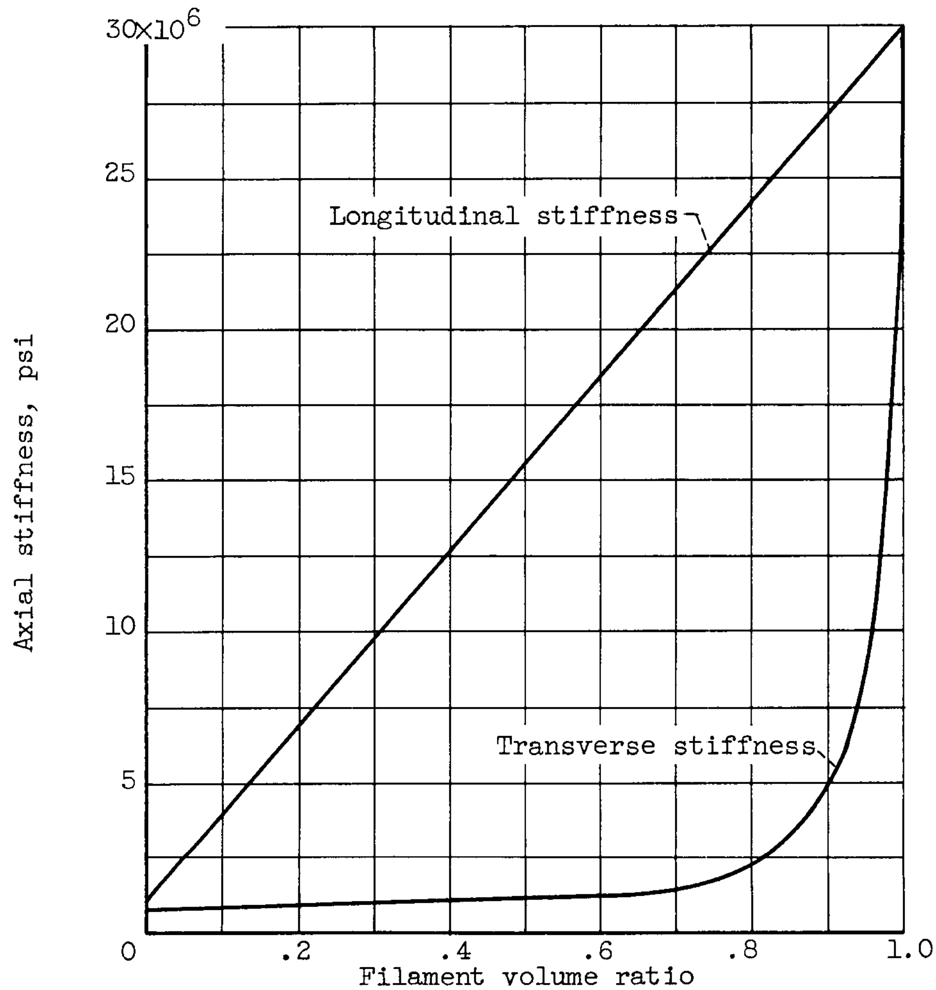


Figure 16. - Axial stiffness comparisons for steel-epoxy composites with square or rectangular filaments. Initial modulus of elasticity of fiber, 30×10^6 psi; initial modulus of elasticity of matrix, 0.4×10^6 psi; Poisson's ratio of matrix, 0.34 (ref. 33).