N71-21228

NASA TECHNICAL MEMORANDUM

NASA TM X- 52993

NASA TM X- 52993

A STUDY OF THE REQUIRED CRITICAL ASPECT RATIO OF FIBERS IN COMPOSITES INTENDED FOR STRESS-RUPTURE APPLICATIONS

by R. W. Jech
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Second Annual Conference on Composite Materials:
Testing and Design sponsored by the American
Society for Testing and Materials
Anaheim, California, April 20-22, 1971

A STUDY OF THE REQUIRED CRITICAL ASPECT RATIO OF FIBERS IN COMPOSITES INTENDED FOR STRESS-RUPTURE APPLICATIONS

by R. W. Jech

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

ABSTRACT

The observed critical aspect ratio for pull-out specimens of tungsten wire and a copper matrix tested in stress-rupture at 649 and 816 C was slightly greater than for tension tests at the same temperature. Time for failure of the stress-rupture specimens was controlled by the properties of the fiber (tungsten) at aspect ratios greater than the critical aspect ratio and by the properties of the matrix (copper) at aspect ratios less than the critical ratio.

KEY WORDS: fiber reinforced composites, aspect ratio, stress-rupture

INTRODUCTION

Fiber reinforced composites continue to be the subject of intensive investigation as a useful material in critical aircraft and spacecraft applications where high strength to weight ratio and modulus to weight ratio are needed. Many of the projected applications for fiber reinforced composites involve use temperatures and times at which failure by creep or stress-rupture could limit their useful life. Stress-rupture and creep of composites in which the reinforcing fibers were continuous through the length of the composite have been studied. These studies demonstrated

TM X-52993

that the superior stress-rupture strength of fibers could be utilized in composites. An analytical study of the stress-rupture and creep properties of continuous tungsten fiber-copper composites as they relate to the stress-rupture and creep properties of the constituents was carried out by McDanels, Signorelli, and Weeton (1).

Much less has been published concerning the stress-rupture and creep properties of short-length or discontinuous fiber reinforced composites. Discontinuous fibers may come in several forms, the most obvious being high-strength whiskers. Another, less obvious form of discontinuous fiber, are filaments which have been broken during composite fabrication or which were cut during component fabrication.

Earlier data (2) had shown that short-length fibers could be used effectively in fiber reinforced composites. In such composites the transfer of load from one fiber to the next was by shear through the matrix. Therefore, any condition, such as increased temperature, that reduced the shear strength of the matrix would result in property degradation of the composite and failure would occur by fibers pulling out of the matrix rather than by tensile failure of the fiber (3). In his study of the creep of discontinuous fiber reinforced composites, Kelly (4) indicated that only pull-out was observed in creep of short-fiber composites. However, the short fiber lengths used in his study were chosen to be near the minimum length necessary for short-time tensile failure of the fiber at the test temperature utilized. If the fiber length necessary for reinforcement in creep or stress-rupture were greater than that for short-time tension, the failure would have been by pull-out and would have led to his conclusion that the matrix controlled the creep rate.

The objectives of this study were to determine the aspect ratio of fibers necessary to reinforce composites for stress-rupture applications and to compare these ratios with those required for reinforcement of composites for short-time tension applications.

A pull-out specimen designed to simulate the conditions in a composite containing tungsten fiber in a copper matrix was used. Short-time tensile tests were conducted at 649 and 816 C. Stress-rupture tests were run at the same temperatures for times up to 100 hours.

MATERIALS AND PROCEDURE

Specimen Configuration

An ideal discontinuous composite would contain uniaxially oriented fibers such as those shown in Figure 1(a), with the long axis of the fiber parallel to the long axis of the specimen. The fibers would be bonded to the matrix and separated from each other by the matrix. Ideally, the fibers would overlap each other uniformly so that there would be the least possible number of fiber discontinuities at any cross section.

Figure 1(b) shows a sketch of the single fiber pull-out specimen used to simulate the conditions around a fiber in a composite containing about 70 volume percent fibers. In the figures, ℓ refers to the length of the fibers in a composite and L to the embedded length of the fiber in a pull-out specimen. The embedded length (L) of a fiber in a pull-out specimen would be equal to one half the length (ℓ) of a fiber in an actual composite. This is because in a composite load was transmitted from fiber to fiber by shear in the matrix, while in a pull-out specimen the load was applied directly to the fiber by gripping one of its ends. The interfiber distance (IFD) would be the thickness of the matrix between the fibers. Here a slight difference would exist between the pull-out specimen and the actual composite. In the pull-out specimen the nearest neighbor fibers would be represented by the inner surface of the hole drilled in the button. The distance between the fiber surface and the hole I.D. would be constant and therefore the IFD would be constant. In a composite containing fibers of a circular cross section arranged in a hexagonal array, there would probably be less restraint of the matrix than in a pull-out specimen with an equal IFD. However, the trends observed in the pull-out specimens should be helpful in understanding the behavior of actual composites.

Testing

With the button of the pull-out specimen held in a special fixture and the load applied from the free end of the wire, specimen failure took place by one of two modes: tensile failure of the wire or pull-out failure of the wire. Specimens with an aspect ratio less than the critical aspect ratio failed by pull-out. Specimens with an aspect ratio greater than the critical ratio failed in the wire. Figure 2(a) to (c) show specimens prior to testing, a specimen which had failed in the wire ($L/D > L_c/D$), and a specimen which had failed by pull-out ($L/D < L_c/D$). More specific details of the specimen configuration, preparation and testing were published in reference 5.

Short-time tensile pull-out tests were conducted using a screw driven, constant-crosshead-speed tensile machine. A furnace equipped with quartz heating lamps was used to heat the specimens. A protective blanket of flowing helium helped to minimize oxidation.

Stress-rupture pull-out tests were run in equipment designed so that the long time tests could be conducted in vacuum (10^{-3} mm Hg) to limit specimen oxidation. Load was applied to the specimen by direct weight loading and failure time was recorded to the nearest 0.01 hour by a timer when the falling weight actuated a microswitch.

RESULTS

Tension Tests

Typical results for short-time tension pull-out tests conducted at 649 and 816 C are shown in Figure 3 where the failure load and mode of specimens of various aspect ratios was plotted as a function of test temperature. In Figure 3 the horizontal lines are the average failure load for the tungsten wire at the test temperature. The aspect ratio corresponding to the "knee" of the curve was defined as the critical aspect ratio (L_c/D). The results indicated that for the tungsten wire-copper specimens tested, the critical aspect ratio in tension was 15.0 at 649 C and 19.8 at 816 C.

Stress-Rupture Tests

Typical results of stress-rupture tests run at 816 C on tungsten wire-copper specimens are shown in Figure 4 (a-c). The only difference between this plot and that for short-time tension tests (fig. 3) was that failure time at constant stress was plotted in the latter instead of failure load. The definition of the critical aspect ratio remained the same. The "knee" still occurred at the critical aspect ratio.

For an average rupture time of 1.37 hours at 816 C, the critical aspect ratio was 20.0, as shown in Figure 4(a). For an average rupture time of 10.33 hours the critical aspect ratio was 23.0 (fig. 4(b)) and for an average rupture time of 42.31 hours the critical aspect ratio was 27.5,

Figure 4(c). Similar trends at different numerical values were observed for tests run at 649 C.

Our results show that the critical aspect ratio of fibers necessary for reinforcement in a discontinuous fiber composite composed of tungsten wire in a copper matrix increased with rupture time as well as with temperature. A summary of the results of stress-rupture tests performed at 649 and 816 C is shown in Figure 5. At 649 C the critical aspect ratio in short-time tension was 15.0. For the same material combination having a stress-rupture life of 79 hours it was necessary to increase the fiber aspect ratio to 19.0. Similarly, at 816 C the critical aspect ratio for stress-rupture failure in 42 hours increased by almost 39 percent, from 19.8 to 27.5, over that required in tension tests.

DISCUSSION

It was expected that the critical aspect ratio in stress-rupture would differ from that for short-time tensile applications. It was found, however, that the difference was relatively small for rupture lives of 100 hours compared to that required for short-time applications at the same temperature. As shown in Figure 5, at 816 C, which is 80 percent of the melting point of copper, the critical aspect ratio for a 100 hour stress-rupture life was only 27.5. Extrapolation of the data indicates that for 1000 hours life the critical aspect ratio would be approximately 31. If a composite were made using 0.254 mm tungsten wire in a copper matrix, the wire would have to be only 1.57 cm long to provide reinforcement for 1000 hours at 816 C, compared to 1.00 cm in tension. It has been estimated by others, although not documented, that much higher aspect ratios would be necessary for stress-rupture applications.

Figure 6 shows a family of curves for tungsten-copper which illustrates how the critical aspect ratio changes as a function of temperature. These curves were obtained by crossplotting the line intercepts 1, 10, 100, and 1000 hours in Figure 5. Figure 6 shows the moderate aspect ratios necessary to accomplish reinforcement for stress-rupture life of as much as 1000 hours at 816 C. Equally important was the change in the critical aspect ratio as the temperature was increased.

Different combinations of fiber and matrix would likely result in different absolute values and rates of change, depending on the properties of the constituents used in the composite. Each materials combination is unique, but the general trends are expected to remain the same for other materials combinations.

The stress-rupture properties of the fiber and the matrix not only determine the critical aspect ratio, but the stress-rupture properties of the composite as well. In reference 4, which was a study of tungsten wire in a silver matrix, it was concluded that the matrix controlled the creep properties of the composite. The results of our investigation suggest that this conclusion be modified. In our investigation we used pull-out specimens to examine stress-rupture failure, which is a creep related phenomenon. When the aspect ratio of the fiber in the pull-out specimen was below the critical aspect ratio and the stress on the matrix was sufficiently high to cause shear stress-rupture failure of the matrix, pull-out occurred. The time required for failure was a function of the stress on the matrix and its creep rate. At fiber lengths greater than the critical length and where fiber fracture occurred, the fiber properties controlled the rupture behavior of the composite. This had already been shown for continuous length fiber composites (1). The fiber length selected for use in reference 4 was nearly equal to that necessary for short-time tensile pull-out. As might be expected with fibers less than the critical length for rupture tests, the specimen failed by pull-out, where the matrix does control the creep rate and failure time.

To predict the critical aspect ratio for fibers in a composite based upon the known properties of the constituents, the properties of the three major parts of the composite: the fiber, the matrix, and the fiber-matrix interface, should be known for the condition in which they exist in the composite.

Tests can be made on fibers which have been heat treated to duplicate the thermal history of the fibers in the composite. Fibers can also be tested after removal from an already fabricated composite. Both methods have been used by various investigators.

Determination of the properties of the matrix is more difficult. Transfer of the load from one fiber to the next is by shear through the matrix. Accurate determination of the pure shear properties without errors due to restraint is difficult. Furthermore, in fiber reinforced composites tested in stress-rupture or creep, the matrix is subjected to shear creep. This type of data is almost nonexistant.

In addition, the effect of the bond or interface between the fibers and the matrix may alter the matrix properties. It has been shown previously (3) that the matrix adjacent to the fiber was restrained and had properties considerably different from the bulk properties of the matrix. Any such change in stress state could or would be expected to have a pronounced effect on the critical aspect ratio. These complicating factors have prevented us from making the desired predictions. More test data and a more complete understanding of the stress state existing in the composite are necessary.

CONCLUSIONS

This investigation of the critical aspect ratio of fibers necessary to reinforce composites for stress-rupture applications and compare them to the critical aspect ratios necessary for short-time tensile applications has led to the following conclusions:

1. The critical aspect ratio of fibers used to reinforce composites for stress-rupture applications was only slightly greater than for short-time tensile applications. At 816 C the critical aspect ratio for short-time tensile applications was 19.8, while for a stress-rupture life of 100 hours the critical aspect ratio was 27.5. In terms of absolute lengths a 0.254 mm fiber would have to be 1.00 cm long for short-time tensile reinforcement at 816 C and 1.39 cm long for stress-rupture application of 100 hours at the same temperature.

2. When the aspect ratio of the reinforcing fibers was below the critical aspect ratio, time to failure of the composite was controlled by the shear creep properties of the matrix. When the fibers had an aspect ratio greater than the critical aspect ratio, failure time of the composite was controlled by the creep properties of the fiber.

REFERENCES

1. McDanels, D. L., Signorelli, R. A., and Weeton, J. W., "Analysis of Stress-Rupture and Creep Properties of Tungsten-Fiber-Reinforced Copper Composites," NASA TN D-4173, National Aeronautics and Space Administration, Sept. 1967.
2. Jech, R. W., McDanels, D. L., and Weeton, J. W., "Fiber Reinforced Metallic Composites." Re. MET 661-601, Syracuse University Research Institute, 1959, pp. 116-143.
3. Jech, R. W. and Signorelli, R. A., "The Effect of Interfiber Distance and Temperature on the Critical Aspect Ratio in Composites," NASA TN D-4548, National Aeronautics and Space Administration, May, 1968.
4. Kelly, A. and Tyson, W. R., in High-Strength Materials, V. F. Zackay, Ed., Wiley, New York, 1965, Chapter 13.
5. Jech R. W., "Influence of Fiber Aspect Ratio on the Stress-Rupture Life of Discontinuous Fiber Composites," NASA TN D-5735, National Aeronautics and Space Administration, Apr. 1970.

E-5407

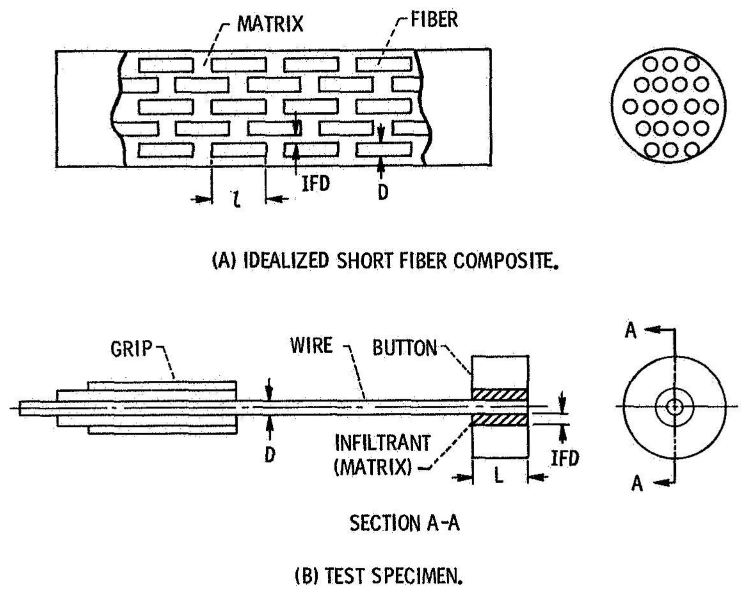

Figure 1. - Comparison of test specimen and short fiber composite.

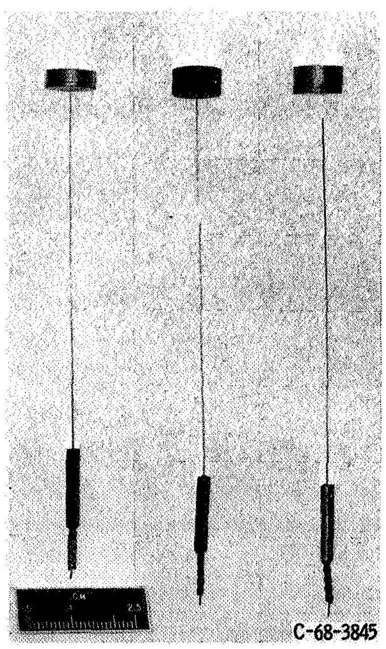

Figure 2. - Stress-rupture specimens.

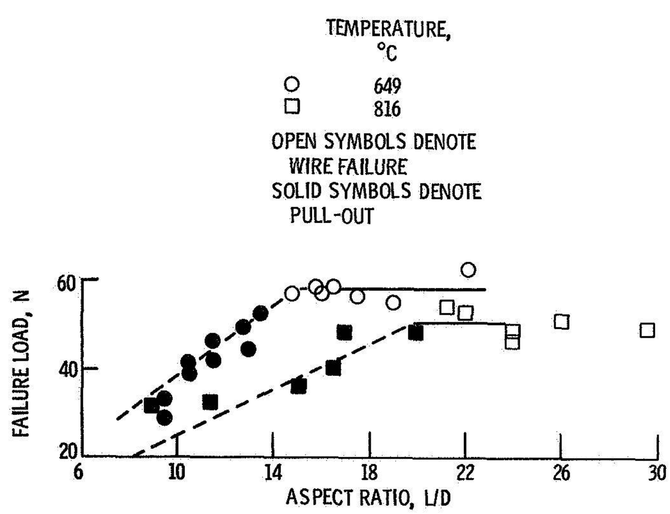

Figure 3. - Failure load and mode at various aspect ratios for tungsten wire - copper, short-time tension tests.

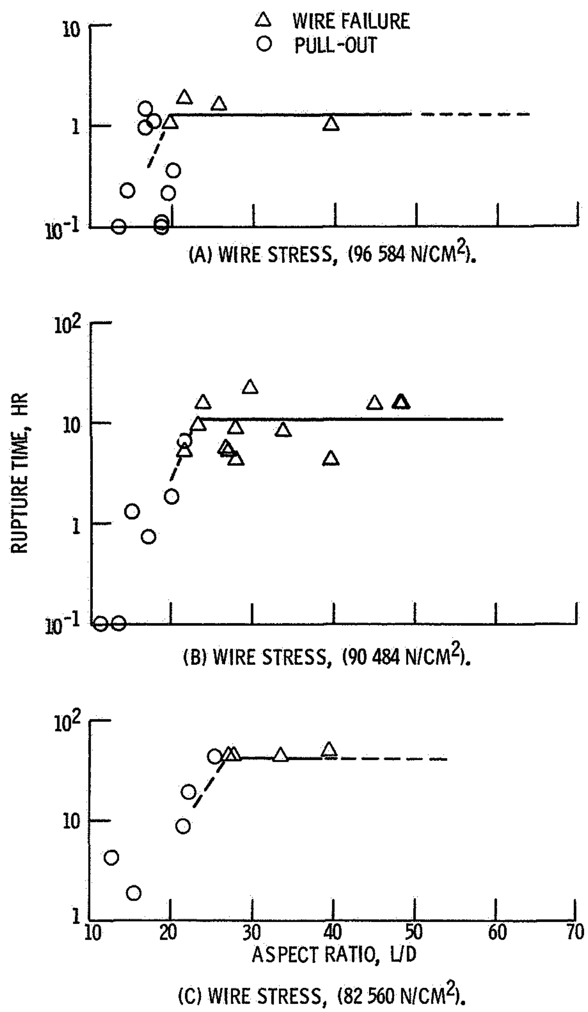

Figure 4. - Failure time and mode at various aspect ratios for tungsten wire - copper pull-out specimen. Test temperature, 816° C.

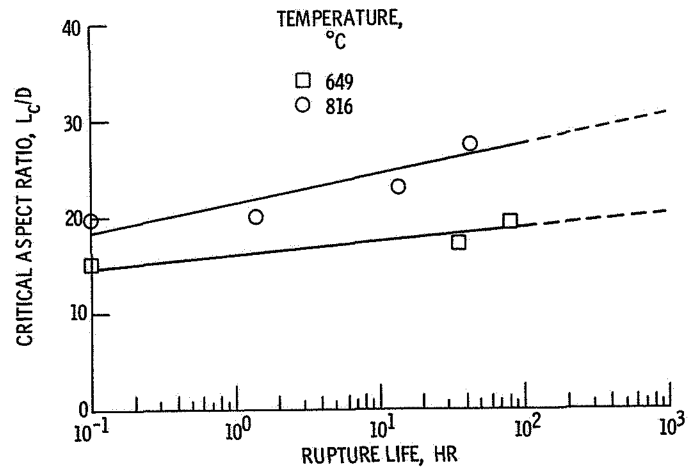

Figure 5. - Critical aspect ratios of tungsten wire - copper pull-out specimens tested in stress-rupture at 649° and 816° C.

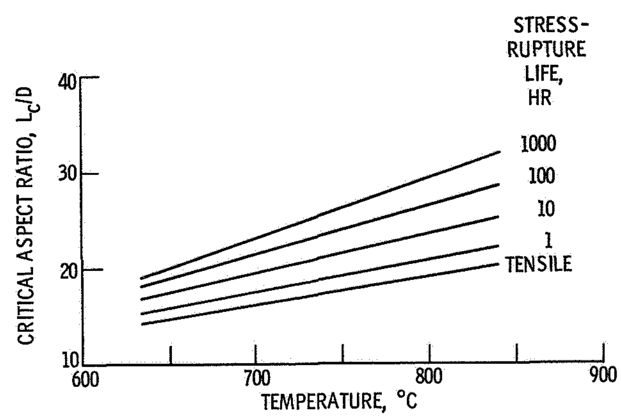

Figure 6. - Calculated critical aspect ratios of tungsten wire - copper pullout specimens in stress-rupture at 649° and 816° C.