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THE EFFECT OF INTERFIBER DISTANCE AND TEMPERATURE ON THE CRITICAL ASPECT RATIO IN COMPOSITES

by Robert W. Jech and Robert A. Signorelli

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ABSTRACT

The effect of interfiber distance and temperature on the critical aspect ratio (minimum fiber length to diameter ratio) in a fiber composite was examined using a modified pullout test. Tungsten-wire - copper, iron-wire - lead, and iron-wire - cadmium specimens were used. Variation of the critical aspect ratio as a function of interfiber distance was determined for the iron-lead and iron-cadmium systems. Critical aspect ratio as a function of temperature was determined for the tungsten-copper system. Reduction of the interfiber distance increased the apparent shear strength of the matrix as indicated by a reduction of the critical aspect ratio. A rapid increase in the critical aspect ratio was noted at test temperatures in excess of 1000° F (540° C).

THE EFFECT OF INTERFIBER DISTANCE AND TEMPERATURE ON THE CRITICAL ASPECT RATIO IN COMPOSITES*

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SUMMARY

Effects of interfiber distance and temperature on the critical aspect ratio (minimum fiber length-to-diameter ratio) in a discontinuous fiber reinforced composite were studied. A modified pull-out test was used. Specimens consisted of tungsten-wire - copper, iron-wire - lead, or iron-wire - cadmium.

The critical aspect ratio as a function of interfiber distance was studied using iron-wire - lead and iron-wire - cadmium samples and interfiber distances in the range from 0.1 mil (0.0003 cm) to 5.0 mils (0.0127 cm). Decreasing the interfiber distance decreased the critical aspect ratio. This suggested an increase in the apparent shear strength of the matrix. The shear strength of lead increased 825 psi (5.68 MN/m^2); the shear strength of cadmium 900 psi (6.20 MN/m^2).

The effect of temperature was studied using tungsten-wire - copper. Tests were conducted at temperatures up to 1500° F (816° C). The critical aspect ratio increased as the test temperature increased. The change was most rapid at temperatures above 1000° F (538° C). Data suggested that wires less than 1 inch (2.54 cm) long could be used at a temperature equal to 0.8 of the melting point of the copper.

INTRODUCTION

Fiber reinforced composites have received a good deal of attention in recent years because they offer the opportunity to provide structural members with unusually high

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tensile strength. Much of the research in materials of this type has been concerned with composites in which the reinforcing fiber is continuous and extends through the entire length of the specimen. Fibers of practical value, however, may not necessarily be available in long enough lengths for some composites. For this reason the mechanical properties of composites in which the reinforcement consists of short length fibers are of interest.

Theoretical (ref. 1) and experimental (refs. 2 and 3) investigations of such composites have been made. Early experimental results at NASA have shown that short length, discontinuous wires could be utilized as reinforcement in composites. It was also shown (ref. 3) that the efficiency of discontinuous fiber reinforcement is a function of the ratio of the fiber length to fiber diameter (aspect ratio). The aspect ratio below which the fiber is no longer stressed to its ultimate tensile strength is the critical aspect ratio.

A direct way to approximate the critical aspect ratio is by using the pull-out test. Work of this type has been done (ref. 3) using wire embedded to varying depths in the matrix material. Our investigation of the critical aspect ratio was designed to explore variables for which little experimental data has been obtained. For example, the effect of interfiber distance on the critical aspect ratio has not been studied. Decreasing the thickness of the matrix between fibers could increase the stress required to cause pull-out by acting in a fashion similar to decreasing the matrix grain size. Or, as reported in reference 4, by triaxial strengthening, which is a constraint of the matrix between fibers having a greater resistance to deformation.

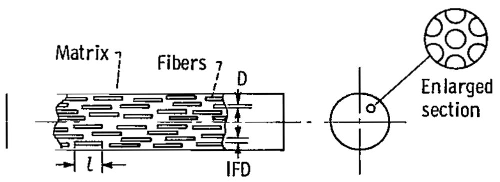
The objective of our program was to determine the effect of temperature and interfiber distance on the critical aspect ratio utilizing a model system and the pullout test. Tungsten wire and iron wire were used as the fibers while copper, lead, or cadmium were used as the matrix material. A specimen configuration designed to simulate conditions around one fiber in a composite was used.

Tungsten-wire - copper matrix specimens were tested at temperatures up to 1500° F (816° C). Specimens of iron wire and lead and iron wire and cadmium with interfiber distances from 5 to 0.1 mil (0.0127 to 0.0003 cm) were tested at room temperature. In addition, a series of iron-wire - lead specimens was photographed during tensile testing in order to study the deformation characteristics of the wire and matrix under conditions of varying stress.

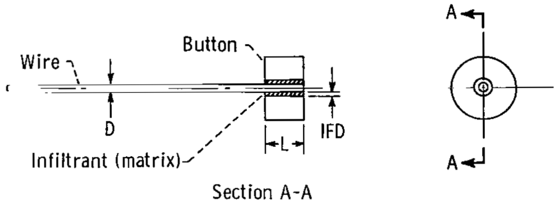
MATERIALS, APPARATUS, AND PROCEDURE

Specimen Configuration

In composites containing discontinuous, uniaxially oriented fibers (fig. 1(a)) the



(a) Idealized short-fiber composite.



(b) Test specimen.

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

short-length fibers are surrounded by the matrix with the long axis of the fibers oriented parallel to the long axis of the specimen. Ideally, the fibers are bonded to the matrix and separated from each other by the matrix with the fibers randomly overlapping.

Figure 1(b) shows a sketch of the test specimen used in this investigation in which the conditions occurring around one fiber in a composite were simulated. In the figures, L and l refer to the length of the fiber in the test specimen and in the composite, respectively. The length of the fiber L in the test specimen is equal to one-half the length of the fiber l in an actual composite. This is because, in the test specimen, the load is applied to the fiber by gripping one end of the fiber. In the composite, load is transmitted to the fiber from both ends by shear through the matrix. The diameter of the fiber is represented by D in both cases. In the remainder of this report the aspect ratios (L/D) reported are those of the test specimen and must be increased by a factor of two when referring to a composite. The interfiber distance (IFD) is the thickness of the matrix between the fibers. Here, again, a slight difference exists between the test specimen and the actual composite. In the test specimen the nearest neighbor fibers are represented by the surface of the hole drilled in the button. The distance between the fiber surface and the hole surface is constant. In a composite containing fibers of a circular cross section, the interfiber distance varies. It is not as easily defined as in our test specimen. However, the trends observed in the model will be helpful in understanding the behavior in a composite.

Variations in properties due to misalinement of the fiber from the tensile axis and alloying effects are other factors which could influence the critical aspect ratio (ref. 5). In the present study alinement was not a problem because of the very close fit of the wire in the drilled hole; alloying effects were minimized by selection of suitable materials

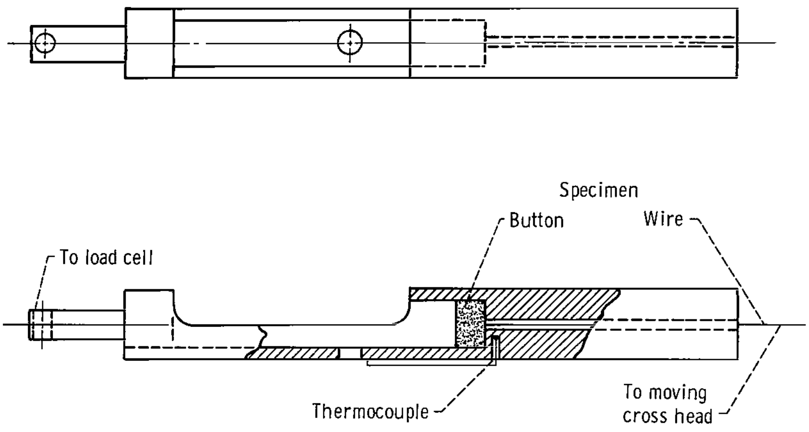
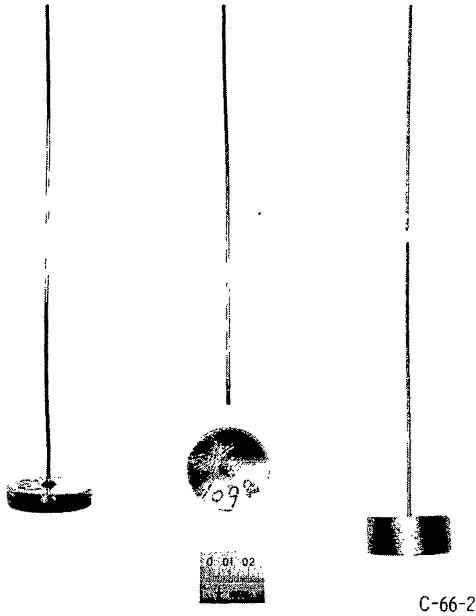


Figure 2. - Tensile test fixture.



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(a) Before testing. (b) Pullout failure. (c) Wire failure.

Figure 3. - Aspect ratio test specimens.

combinations. Cadmium and lead were used as infiltrants (matrix) because of their relative insolubility in iron, which was used as the fiber. They also differ in crystal structure. Lead is face centered cubic, and cadmium is hexagonal close packed. Copper was used in combination with tungsten because of their mutual insolubility. Also, a good deal of information on composites of the tungsten-copper model system is available for comparison.

When mounted and tested in a fixture such as the one shown in figure 2, specimen failure took place by either of two modes: pullout, that is, shear failure in the infiltrant or at the interface, or tensile failure of the wire. Specimens with an aspect ratio less than the critical aspect ratio failed by pullout. Those having an aspect ratio greater than the critical aspect ratio failed by tensile failure of the wire. Figure 3(a) shows a specimen prior to testing. Figure 3(b) shows a specimen that has failed by pullout ($L/D < L_c/D$). Figure 3(c) shows a specimen that has failed by fracture of the wire ($L/D > L_c/D$).

Specimen Preparation

Ingot iron-lead. - Ingot iron wire was prepared in our laboratory by cold swaging and drawing a 7/16-inch (1. 11-cm) rod to 19. 8±0. 05-mil (0. 0529±0. 00013-cm) diameter. After swaging and drawing, the wire was annealed by heating to 1650° F (899° C) in vacuum and furnace cooling.

Buttons were prepared by cutting lengths of the appropriate thickness from 7/16 inch (1. 11-cm) diameter rod or by punching 7/16-inch (1. 11-cm) diameter disks from ingot iron sheet which had been rolled to the required thickness. This was done so that the properties of the wire and the buttons were as nearly equal as possible.

Holes were drilled in the buttons using American Standard, numbered, high-speed twist drills mounted in a high-precision jeweler's lathe. Final hole size was obtained by using four flute, straight shank precision reamers to remove the final 0. 5 mil (0. 0013 cm). Axiality was maintained by rotating both the button and the drill or reamer during the machining operation. Hole diameters were measured using a microscope and split image eyepiece. This drilling and reaming procedure enabled the preparation of holes of the required size with an accuracy of ±0. 035 mil (0. 000089 cm). The thickness of the buttons was measured to the nearest 0. 1 mil (0. 0003 cm) using a precision micrometer. When these techniques were used, the accuracy of the L/D calculation of specimens having an $L/D = 1$ was ±0. 005.

Buttons and wire were ultrasonically cleaned in acetone and given a light hydrochloric acid etch after which they were assembled as shown in figure 4. Assembled specimens were dipped in a commercial liquid soldering flux and immediately placed in a preheated,

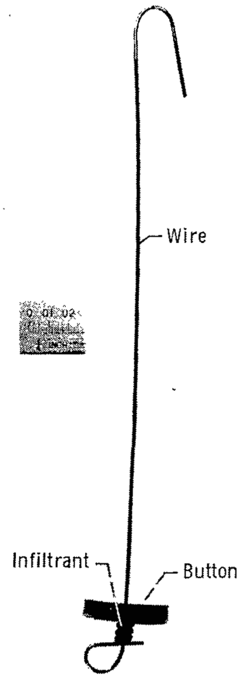

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Figure 4. - Aspect ratio test specimen prior to infiltration.

1000° F (538° C), air atmosphere furnace. They were heated for 5 minutes, removed, and air cooled. During infiltration, the surface tension of the infiltrant centered the wire in the drilled hole. Excess infiltrant was mechanically removed from the specimen before testing. Specimens showing signs of damage were discarded.

Ingot iron-cadmium. - These specimens were made in the same way as the ingot iron-lead specimens.

Tungsten-copper. - Tungsten buttons were made by cold pressing 5-micron tungsten powder into disks of various thickness. These were drilled and sintered for 4 hours at 4200° F (2316° C), in vacuum. Lengths of 10-mil (0.0254-cm) diameter tungsten wire and a spiral of OFHC (oxygen free high conductivity) copper wire were assembled in the same way as the iron-lead specimens. Infiltration was done in a hydrogen atmosphere for 15 minutes at 2200° F (1204° C).

Tungsten-wire - copper specimens were used for elevated temperature tests. They all had a nominal interfiber distance of 1.6 mils (0.0041 cm). Variations of interfiber distance were not attempted because of the difficulty in drilling small holes of high precision in tungsten. This was an even more difficult problem as the thickness of the button increased.

Testing

Tests were conducted using a screw-driven constant crosshead speed tensile machine and a crosshead speed of 0.05 inch (0.127 cm) per minute. For the elevated temperature tests, a furnace equipped with quartz heating lamps was used to heat the specimen. Such a heat source brought the specimens to test temperature very quickly. This, in addition to the flowing helium in the furnace, helped to minimize specimen oxidation during testing.

Shear strengths of cadmium, lead, and copper infiltrants in bulk form, were determined using the double-shear specimen and fixture shown in figure 5. Tests were conducted at room temperature. These materials had been subjected to a thermal history which duplicated, as much as possible, the thermal history of the infiltrant in the actual test specimen. In addition, tests were run on copper at elevated temperature.

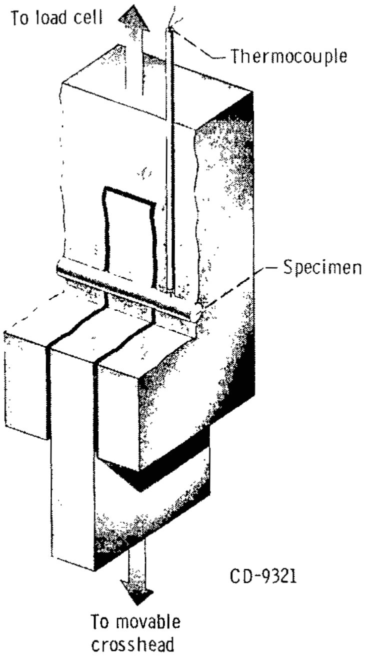


Figure 5. - Shear test fixture; double shear.

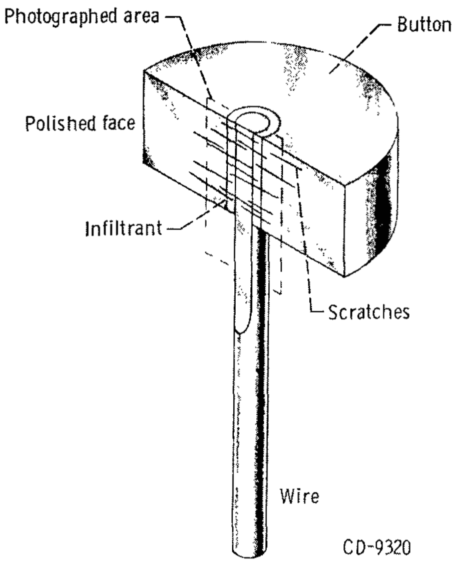


Figure 6. - Deformation study specimen.

Deformation study. - In order to get an indication of the deformation taking place within a test specimen during loading, samples of ingot iron infiltrated with lead were photographed during testing. The specimens were sectioned and polished on a plane parallel to the wire so that the iron-wire - lead and lead-iron button interfaces were exposed while the major portion of the wire remained intact (fig. 6). Lead was plated on the specimen to replace that which had been removed during polishing. Reference marks were scratched on the plated surface using 320 grit paper. The samples were then mounted in a fixture so that the plated surface was exposed. The sample was loaded at room temperature. A crosshead speed of 0.005 inch (0.127 cm) per minute was used to permit sufficient time for photographs to be made. During the course of the test the samples were photographed using a synchronized flash illuminator and a 35 millimeter camera with a lens system which resulted in a 3× magnification on the negative. Exposures were made at 13-second intervals and marks were made on the tensile machine load chart to indicate those points at which photographs were taken.

RESULTS

Room Temperature Pullout Tests

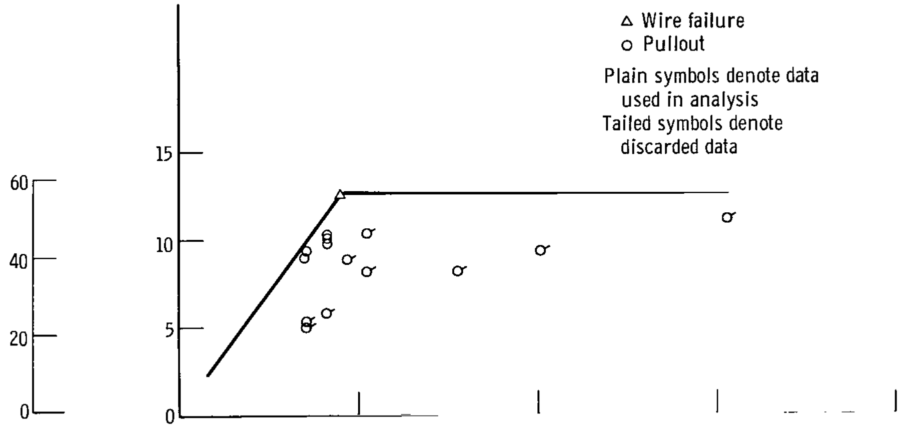
Ingot iron-lead. - A summary of the results of this series of pullout tests is given in table I. The results of individual tests of specimens having varying interfiber distances are plotted in figure 7. In these figures the horizontal line shown for the failure load of the wire is the same in all cases. It is the average of the 275 wire failures in the iron-lead and iron-cadmium specimens. The position of the "knee" of the curve, where, as the specimen aspect ratio is decreased, failure changes from wire fracture to pullout, was taken as the critical aspect ratio. The critical aspect ratio was taken as the intersection of the horizontal wire failure line with a line drawn from the origin to the point of last wire failure, that is, wire failure for smallest aspect ratio.

Some specimens, shown on the figures as tailed symbols, are premature failures. These are the result of incomplete infiltration or weld defects in the wire. Without exception, the specimens which failed prematurely in pullout showed areas on which there was no bond between the infiltrant and the wire. Some wires broke at loads less than that which would normally be expected. These failures were attributed to welds in the wire. Wire was welded during drawing so that long lengths could be processed. Speci-

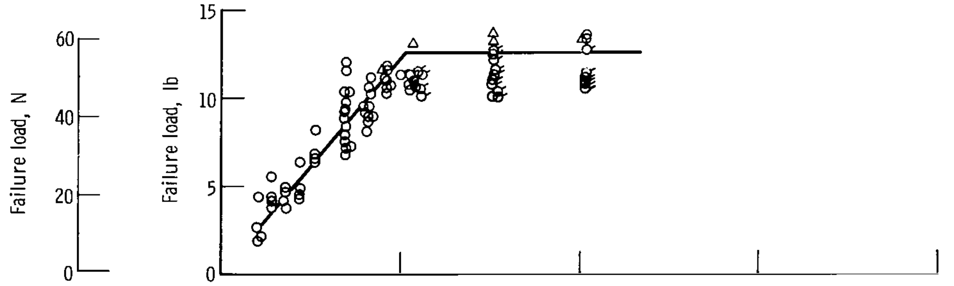
TABLE I. - OBSERVED CRITICAL ASPECT RATIO AND SHEAR STRESS FOR VARIOUS WIRE INFILTRANT COMBINATIONS

[Room temperature tests.]

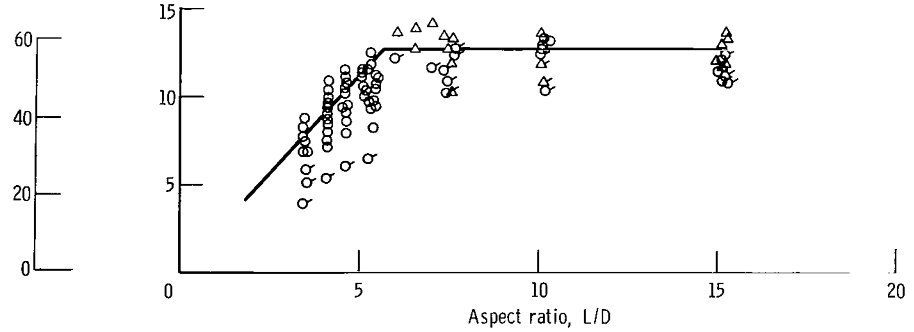
Wire	Infiltrant	Nominal interfiber distance		Observed critical aspect ratio	Shear stress	
		in.	cm		psi	MN/m^2
Tungsten	Copper	0.0016	0.0041	3.0	----	-----
Ingot iron	Cadmium	.0001	.0003	1.6	6400	44.13
		.0002	.0005	1.7	5700	39.30
		.0005	.0013	1.8	5500	37.92
		.001	.0025	1.9	5250	36.20
		.002	.0051	1.9	5250	36.20
		.005	.0127	1.9	5250	36.20
	Lead	.0001	.0003	4.5	2275	15.69
		.0002	.0005	5.1	2000	13.79
		.0005	.0013	5.6	1825	12.58
		.001	.0025	5.8	1775	12.24
		.002	.0051	5.8	1775	12.24
		.005	.0127	6.4	1600	11.03



(a) Interfiber distance, 0.1 mil (0.0003 cm).

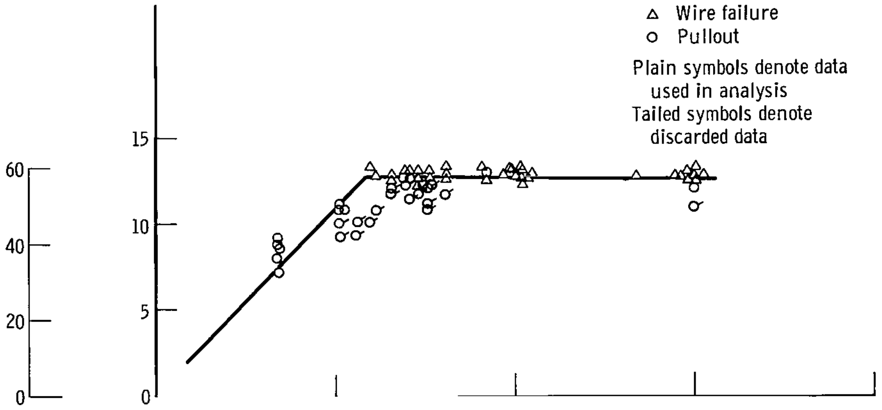


(b) Interfiber distance, 0.2 mil (0.0005 cm).

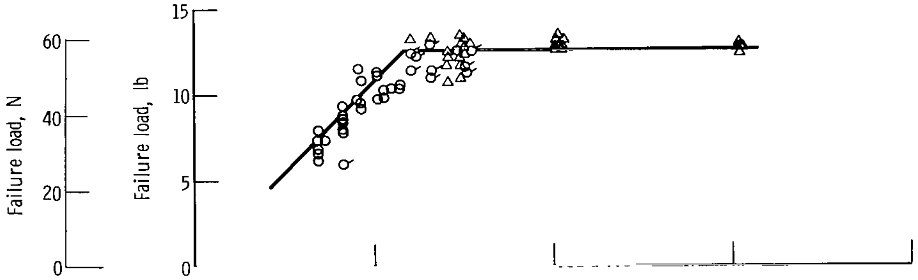


(c) Interfiber distance, 0.5 mil (0.0013 cm).

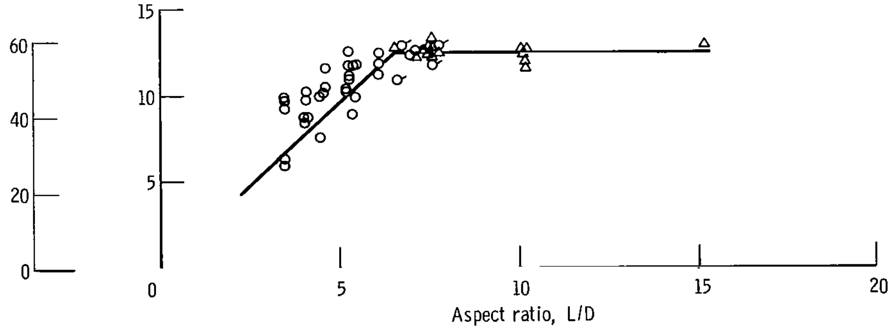
Figure 7. - Failure load and mode at various aspect ratios. Ingot iron-lead; room temperature.



(d) Interfiber distance, 1.0 mil (0.0025 cm).



(e) Interfiber distance, 2.0 mils (0.0051 cm).



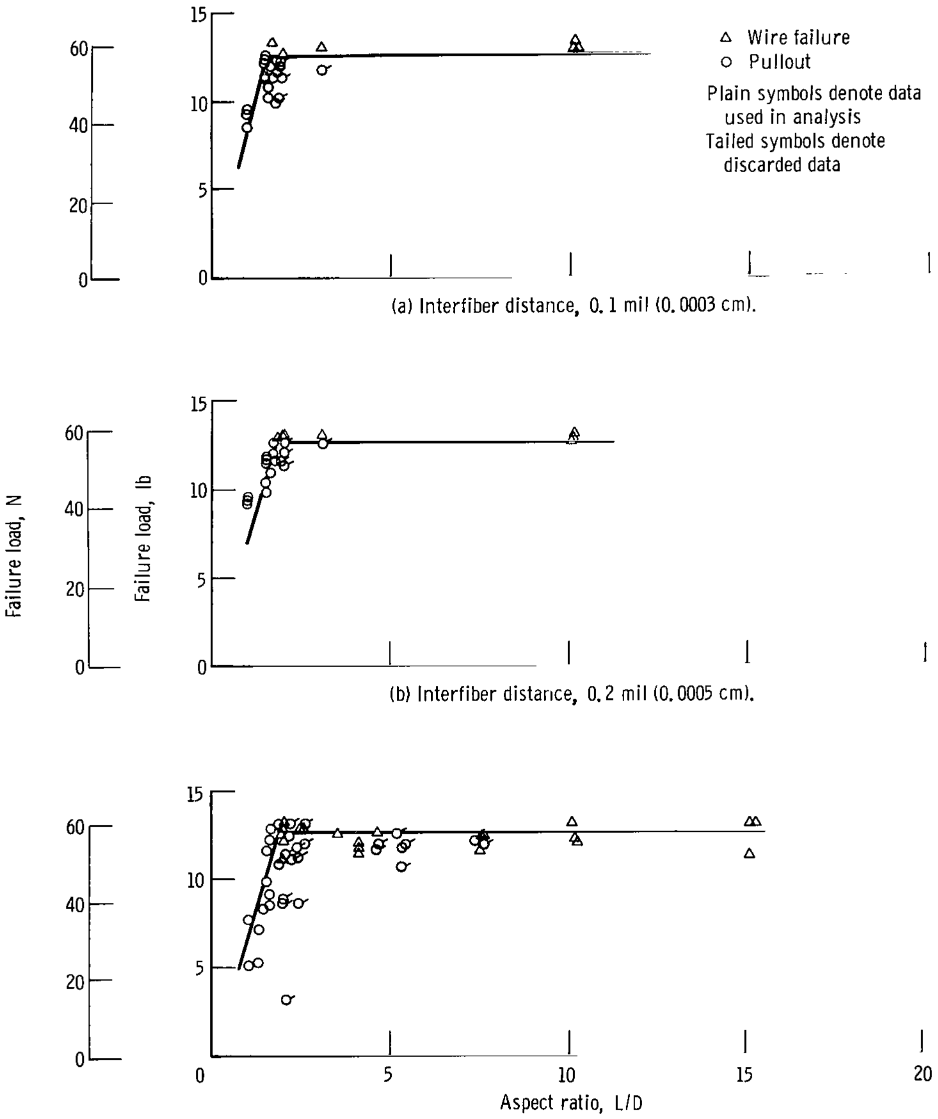
(f) Interfiber distance, 5 mils (0.0127 cm).

Figure 7. - Concluded.

mens with obvious imperfections, shown as tailed symbols were not included in the final results.

The results of the tests on the iron-lead specimens show that, at an interfiber distance of 0.1 mil (0.0003 cm), the critical aspect ratio was 4.5 (fig. 7(a)). As the interfiber distance was increased, the critical aspect ratio increased. At interfiber distances of 0.2, 0.5, 1, 2, and 5 mils (0.0005, 0.0013, 0.0025, 0.0051, and 0.0127 cm) the critical aspect ratios were 5.1, 5.6, 5.8, 5.8, and 6.4, respectively (figs. 7(b) to (f)).

Ingot iron-cadmium. - Figure 8 shows the results of tests conducted on iron wire

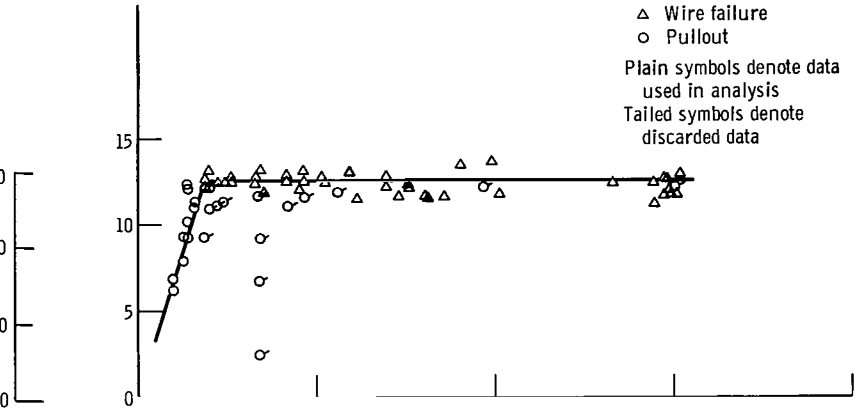


(a) Interfiber distance, 0.1 mil (0.0003 cm).

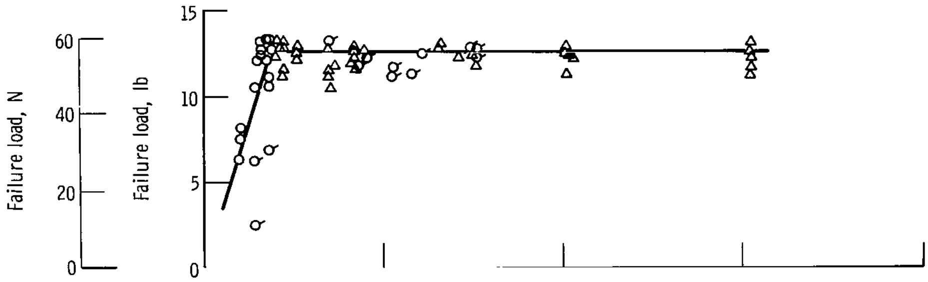
(b) Interfiber distance, 0.2 mil (0.0005 cm).

(c) Interfiber distance, 0.5 mil (0.0013 cm).

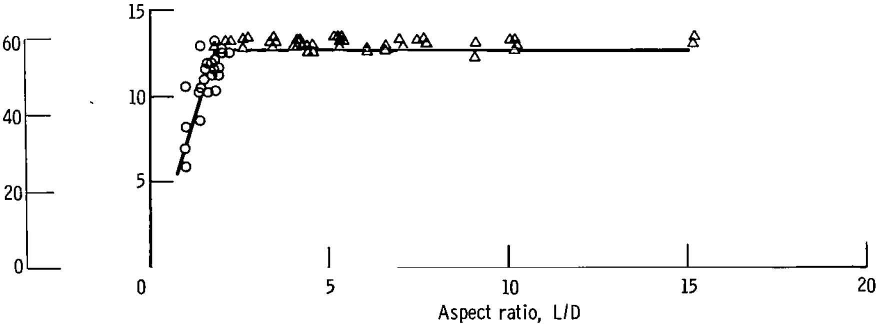
Figure 8. - Failure load and mode at various aspect ratios. Ingot iron-cadmium; room temperature.



(d) Interfiber distance, 1 mil (0.0025 cm).



(e) Interfiber distance, 2 mils (0.0051 cm).



(f) Interfiber distance, 5 mils (0.0127 cm).

Figure 8. - Concluded.

infiltrated with cadmium. These tests were conducted over the same range of interfiber distances as the iron-lead specimens. At 0.1 mil (0.0003 cm) (fig. 8(a)) the critical aspect ratio was 1.6, while at an interfiber distance of 0.2 mil (0.0005 cm) (fig. 8(b)), it increased to 1.8 and 0.5 mil (0.0013 cm) (fig. 8(c)) to 1.9. At interfiber distances of 1, 2, and 5 mils (0.0025, 0.0051, and 0.0127 cm) the critical aspect ratio was constant at 1.9 (figs. 8(d) to (f)).

Tungsten-copper. - Results of room temperature pullout tests on specimens of tungsten wire and copper are shown in figure 9. The critical aspect ratio for these specimens was determined in the same way as for the iron-lead and iron-cadmium specimens. At room temperature the critical aspect ratio for 10-mil (0.0254-cm) tungsten wire infiltrated with OFHC copper was 3.0. The interfiber distance was 1.6 mils (0.0041 cm). The wire failure load shown is the average failure load for all samples which failed by tensile failure of the wire.

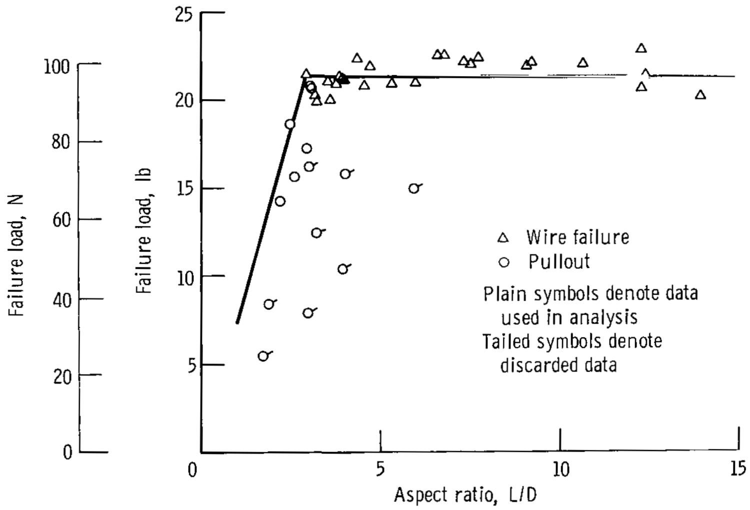


Figure 9. - Failure load and mode at various aspect ratios. Tungsten wire-copper; room temperature; interfiber distance, 1.6 mils (0.0041 cm).

Elevated Temperature Tests

Figure 10 shows the results of elevated temperature tests on specimens on 10-mil (0.0254-cm) tungsten wire and tungsten buttons infiltrated with OFHC copper. The interfiber distance was 1.6 mils (0.0041 cm). These results are also presented in table II.

Results of room temperature tests are included in figure 10. At 600° F (316° C) the critical aspect ratio was found to have increased to just over 3, although, at 900° F (482° C), it is somewhere between 3.9 and 4.7. At temperatures in excess of 900° F

TABLE II. - RESULTS OF TESTS ON TUNGSTEN WIRE-COPPER SPECIMENS

[Elevated temperature tests; nominal interfiber distance, 0.0016 in. (0.0041 cm).]

Failure mode		Aspect ratio	Test temperature	
Wire	Pull-out		°F	°C
	√	2.4	600	316
√		3.4	↓	↓
√		4.5	↓	↓
√		5.6	↓	↓
√		3.8	↓	↓
√		4.8	900	482
√		4.7	↓	↓
	√	2.0	↓	↓
	√	3.1	↓	↓
	√	3.9	↓	↓
√		6.8	↓	↓
√		5.3	950	510
√		6.5	1000	538
	√	4.9	1000	538
√		7.0	1100	593
	√	5.2	1100	593
√		6.4	1200	649
√		8.9	1250	677
	√	6.3	1300	704
√		13.6	1300	704
	√	8.5	1350	732
√		8.6	1350	732
√		8.6	1350	732
	√	6.2	1400	760
	√	13.8	1450	788
√		24.9	1500	816
√		15.3	1500	816
√		15.4	1500	816

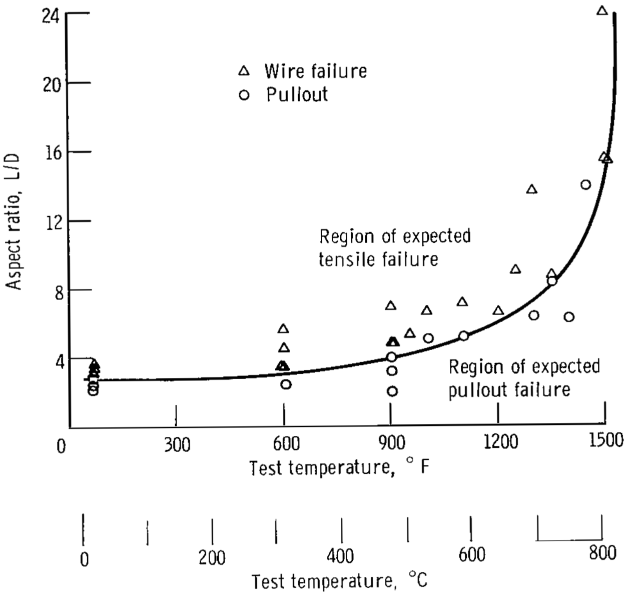


Figure 10. - Critical aspect ratio as function of temperature. Tungsten-copper system; interfiber distance, 1.6 mils (0.0041 cm).

(482° C) the change was rapid, and at 1500° F (816° C) the critical aspect ratio was near 15.

Deformation Study

Figure 11 shows a series of photographs taken during the course of the special tests on iron-lead specimens. Figure 11(a) shows the specimen in the no load condition. The index marks at X extend across the lead from the wire to the button and are relatively straight. Figure 11(b) shows that, as load is applied, deformation begins in the area nearest the application of the load (lower portion of the photograph). Increasing the load (fig. 11(c)) causes deformation farther along the wire. Figure 11(d) shows the section after failure of the lead. The wire has begun to pull out.

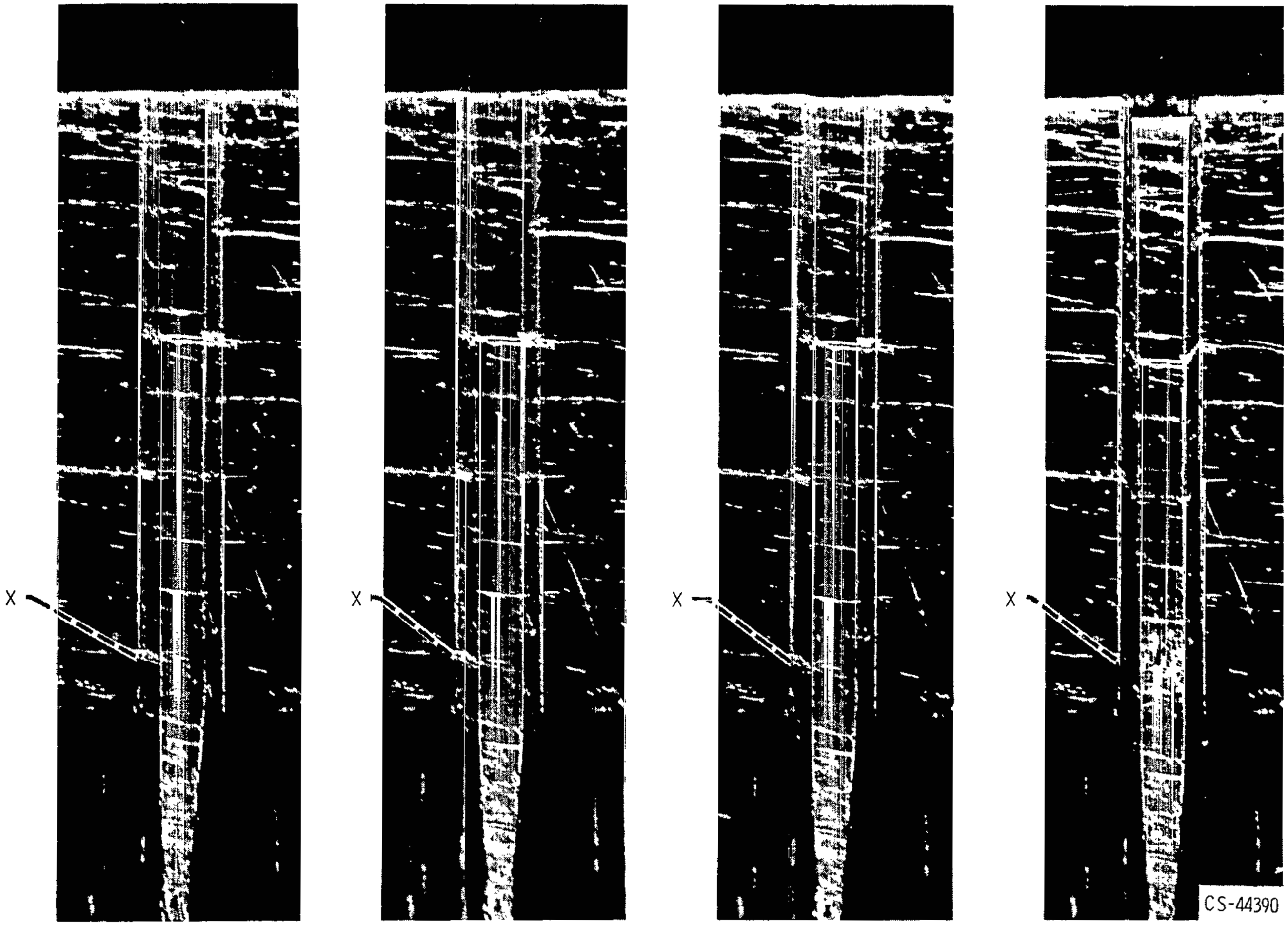
DISCUSSION

Effect of Interfiber Distance

Results of this investigation show that the critical aspect ratio is dependent on the interfiber distance. This can be seen in figure 12, which is a summary plot of the critical aspect ratio as a function of the interfiber distance for specimens of iron-wire - lead and iron-wire - cadmium. For the iron-lead specimens the critical aspect ratio decreases from 6.4 to 5.6 when the interfiber distance was decreased from 5 mils (0.0127 cm) to 0.5 mil (0.0013 cm). When the interfiber distance was reduced to 0.2 mil (0.0005 cm) the critical aspect ratio was decreased to 5.1. A further reduction of interfiber distance to 0.1 mil (0.0003 cm) resulted in a reduction of the critical aspect ratio to 4.5. Tests on iron wire and cadmium show a similar trend (fig. 12), although not as pronounced as the iron-lead specimens. In the case of the iron-cadmium specimens, the critical aspect ratio was decreased from 1.9 to 1.6 when the interfiber distance was decreased from 5 mils (0.0127 cm) to 0.1 mil (0.0003 cm).

Another way to assess the effect of interfiber distance on the critical aspect ratio is to compare the expected critical aspect ratio, based on the bulk properties of the materials, with the critical aspect ratios observed in the tests.

If the following equation is used, it is possible to calculate the critical aspect ratio when the bulk infiltrant and fiber properties are known.



(a) No load.

(b) Low load.

(c) Medium load.

(d) Pullout.

Figure 11. - Sequential photographs of deformation tests. X indicates index.

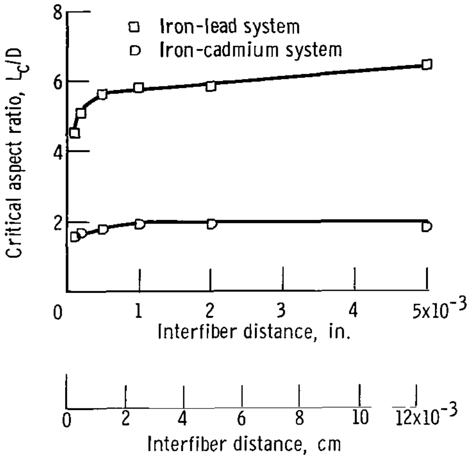


Figure 12. - Observed critical aspect ratio at various interfiber distances.

$$\frac{L_c}{D} = \frac{1}{4}\frac{\sigma_w}{\tau_m} \tag{1}$$

where σ_w is the tensile strength of the fiber and τ_m shear strength of the infiltrant.

Figure 13 shows a plot of the change, in percent, in the critical aspect ratio as a function of interfiber distance. It was arrived at by taking the difference between the critical aspect ratio calculated using equation (1) and the observed critical aspect ratio. The calculated ratio was arrived at using the experimentally determined tensile strength of the wire and the shear strength of bulk specimens of lead or cadmium (table III). The observed critical aspect ratio was taken from the results of the pullout tests.

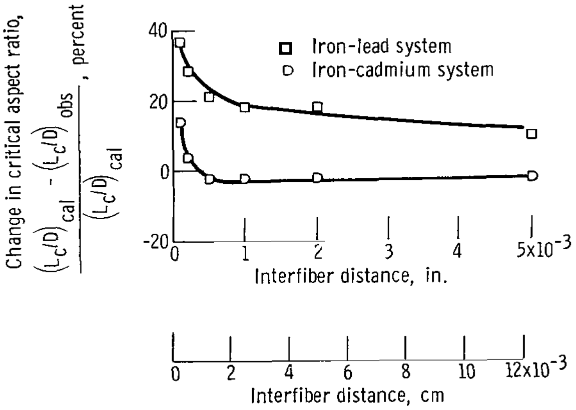


Figure 13. - Change in critical aspect ratio as function of interfiber distance.

TABLE III. - MECHANICAL PROPERTIES OF CONSTITUENTS

(a) Shear strength of infiltrant metals. Rod diameter, 0.135 inch (0.343 cm)

Metal	Condition	Test temperature		Shear strength[a]	
		°F	°C	psi	MN/m^2
Lead	Chill cast	RT[b]	RT	1 450	9.99
Cadmium	Chill cast	RT	RT	5 500	37.92
Copper	Annealed 1 hr at 1500° F (816° C)	RT	RT	20 600	142.04
		300	149	17 150	118.25
		600	316	12 500	86.19
		900	482	8 150	56.19
		1200	649	3 400	23.44
		1500	816	350	2.41

(b) Tensile strength of wire

Metal	Condition	Test temperature		Tensile strength	
		°F	°C	psi	MN/m^2
Ingot iron	Annealed 1650° F (899° C)	RT	RT	40 970	282.49
		RT	RT	218 000	1503.11
Tungsten	Annealed 15 min at 2200° F (1204° C)	300	149	177 000	1220.42
		600	316	137 500	948.06
		900	482	120 000	827.40
		1200	649	112 000	772.24
		1500	816	100 000	689.50

[a] Average of five tests.

[b] RT indicates room temperature.

This plot (fig. 13) shows that a decrease of as much as 38 percent in the critical aspect ratio can be obtained in specimens of iron-wire - lead when the interfiber distance is decreased to 0.1 mil (0.0003 cm). A similar trend in the data for the iron-wire - cadmium may also be seen, although the change in critical aspect ratio is not as pronounced.

Using the same equation it was also possible to calculate the shear stress on the lead or cadmium for specimens which failed by tensile failure of the wire. This is the shear stress to which the infiltrant was stressed without failing. The results of these calculations are plotted in figure 14 as a function of interfiber distance. These data show the

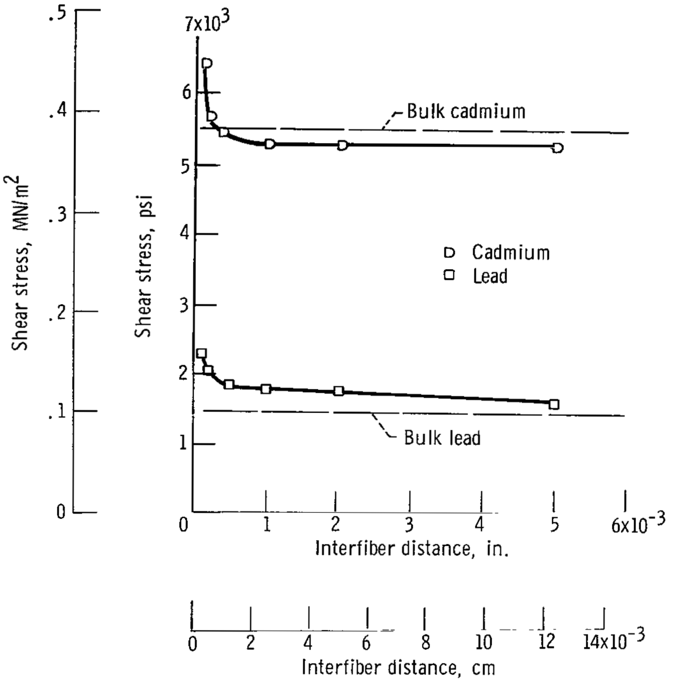


Figure 14. - Shear stress on infiltrant at various interfiber distances.

same general trend seen in the plot of the percent change in critical aspect ratio as a function of interfiber distance (fig. 13).

In the case of lead, the shear stress, at an interfiber distance of 5 mils (0.0127 cm), was about 10 percent greater than the shear strength of the bulk lead. As the interfiber distance was decreased to 2 mils (0.0051 cm) the shear stress on the lead was nearly 22 percent greater than the shear strength of the bulk metal. When the interfiber distance was decreased to less than 0.5 mil (0.0013 cm) the shear stress increased much more rapidly. At an interfiber distance of 0.2 mil (0.0005 cm) the increase was about 38 percent. At 0.1 mil the lead was nearly 57 percent stronger than bulk lead.

Cadmium behaved much like the lead. In the joints having thicknesses less than 0.5 mil (0.0013 cm) the rapid increase in apparent shear strength was again noted. The number of operable slip systems in cadmium (close packed hexagonal) is less than in lead (face centered cubic). It was expected that the cadmium would be more sensitive to triaxial strengthening. This was found to be true. The difference in apparent shear strength was 900 psi (6.20 MN/m^2) for cadmium and 825 psi (5.68 MN/m^2) for lead.

It is generally accepted that strengthening of the soft phase in a joint or composite is due to a buildup of triaxial stresses in the soft phase between the harder, less yielding, second phase. In our investigation the joint in the specimen with an interfiber distance less than 0.001 inch (0.0025 cm) was bridged by only one or two grains. Because of this, the amount of material available to deform and relieve the stress buildup in the joint was severely limited. This resulted in a joint of increased strength. A more complete discussion of this phenomenon may be found in reference 6.

Deformation Tests

There are interesting features to be pointed out in the results of the deformation study on iron-lead specimens (fig. 11). The first is that deformation across the lead from wire to button was not uniform (figs. 11(a) and (c)). Rather, those portions of the lead immediately adjacent to the wire and the button did not deform as much as the remainder. The greatest amount of deformation took place in the middle third of the thickness. This is shown by the S shape of the index marks (X) in figures 11(b) and (c). Initially, these marks were straight (fig. 11(a)). Similar results have been observed in other systems (ref. 7), and they indicate the importance of a good bond between the fiber and the matrix. It would appear that the maximum amount of shear deformation occurred along a plane slightly removed from the interface. As the total shear strain increased, it was localized in that portion of the lead away from the restraining influence of the interface.

Secondly, the shape of the load-deformation curve was of considerable interest. A comparison of the load-deformation curve (not presented herein) with the photographs showed that, even after the specimen had been stressed to its highest stress level, considerable additional energy was expended in causing the wire to finally pull out. From this, it is possible to speculate that the impact resistance of a short fiber composite may be enhanced by allowing some fibers of less than critical aspect ratio to shear and pull out rather than fail in tension.

Effect of Elevated Temperature

The increase in critical aspect ratio as a function of temperature (fig. 10) is of importance because it shows the necessity for obtaining fibers of high aspect ratio for use as reinforcement when the matrix shear strength is low. This is particularly true when the application temperature is high in relation to the softening temperature of the matrix material. Fibers having high strength at high temperature are not enough. A combination of high strength and sufficient aspect ratio must be considered.

Conversely, the results of this series of tests also point out that long wires are not always necessary for use as reinforcement in metal-metal composites; even though they may be intended for application at high temperatures. In the case of the tungsten-copper specimens, wires as short as 0.24 inch (0.61 cm) were sufficiently long to have failed in tension at a temperature equal to 0.8 of the melting point of the matrix. Based on the relation (ref. 3) between fiber length and composite strength, the use of a wire 1 inch (2.54 cm) long would result in a composite utilizing about 90 percent of the full tensile strength of the wire.

CONCLUDING REMARKS

Several investigators (refs. 1 to 3 and 5) have shown the importance of the critical aspect ratio of the reinforcing fibers in a discontinuous fiber reinforced composite. There are several possible methods by which the critical aspect ratio can be altered. One of these is to change the shear properties of the matrix material. Another alternative would be to reduce the fiber strength. Alloying the matrix to increase its strength and thereby reduce the critical aspect ratio has been done (ref. 5), although the alloying elements must be judiciously selected in order to prevent degradation of the fiber properties (ref. 8).

Dispersion strengthening of the matrix offers another possible way of reducing the critical aspect ratio by changing the properties of the matrix. This presents some interesting possibilities with regard to increased temperature resistance, but nothing has appeared in the literature to suggest that such a method is being investigated.

A third method, and one which was studied in this investigation, is triaxial strengthening of the matrix. Early work (ref. 4) has shown that the shear strength of a metal could be increased when it is present between two metals having a higher yield strength. It has also been found (ref. 9) that both silver and lead responded to such a strengthening mechanism.

The results of our investigation have shown a dependence of critical aspect ratio on interfiber distance. Because critical aspect ratio is directly related to the shear strength of the matrix, it indicates that, as the spacing between the fibers in a composite is decreased, the critical aspect ratio decreases. Similarly, changing the strength of the matrix can result in a change in the fiber content-strength curve. Normally, in systems showing mutual insolubility, the relation between fiber content and tensile strength is linear. At high fiber contents, depending on fiber size and cross-sectional geometry, the matrix between fibers could become very thin and the matrix properties change. At this fiber content the properties of the composite would deviate from linearity. Such a concept has been proposed (ref. 10) and from the results of our tests would appear to be valid. Because the attainment of very small, uniform interfiber distances is difficult with fibers of a circular cross section, other cross sections must be considered. Fibers of square or hexagonal cross section could be packed so that a much more uniform interfiber spacing could be achieved.

There are possible advantages to be obtained from achieving small interfiber distances. There may be disadvantages as well. It has been shown (ref. 11) that the ductility of a composite may be adversely affected by very small interfiber distances.

Utilization of the pullout method to determine the effect of interfiber distance and temperature on the critical aspect ratio was practical. However, this method has limitations. The values of critical aspect ratio cannot be taken as absolute values in all cases. Under those conditions where work hardening of the matrix is not encountered, it may be used. When appreciable work hardening is encountered the critical aspect ratio values obtained tend to be smaller than are required for actual composites.

CONCLUSIONS

This investigation of the effect of interfiber distance and temperature on the critical aspect ratio of fibers necessary for reinforcement in a discontinuous fiber composite led to the following conclusions:

1. Interfiber distance had an effect on the critical aspect ratio. As the interfiber distance was reduced, the critical aspect ratio decreased for both the iron-lead and iron-cadmium systems. For example, in the iron-lead system reduction of the interfiber distance from 1 mil (0.0025 cm) to 0.1 mil (0.0003 cm) decreased the critical aspect ratio from 5.8 to 4.5.

2. The apparent shear strength of ductile matrix materials increased with decreasing distance between high modulus fiber materials. The apparent shear strength of lead (face centered cubic crystal structures) increased from 1450 psi (9.99 MN/m^2) when tested in the bulk form (0.135 in. (0.343 cm)) to 2275 psi (15.69 MN/m^2) when tested as an infiltrant 0.1 mil (0.0003 cm) thick. Under the same conditions cadmium (close packed hexagonal) shear strength increased from 5500 psi (37.92 MN/m^2) to 6400 psi (44.13 MN/m^2).

3. The critical aspect ratio increased with increased temperature. For example, the critical aspect ratio of the tungsten-copper specimens increased rapidly, particularly at temperatures in excess of 1000° F (538° C). However, the critical aspect ratios obtained indicated that relatively short wires could be used to reinforce copper at temperatures as high as 0.8 of the melting point of copper.

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