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

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TECHNICAL PAPER proposed for presentation at 12th Annual Symposium ~~Advanees~~ in ~~Structural~~ Composites, sponsored by the Society of Aerospace Material and Process Engineers
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ABSTRACT

The effect of interfiber distance and temperature on the critical aspect ratio (minimum length to diameter ratio) in a fiber composite was examined using a modified "pull-out" test. Tungsten fiber-copper, iron fiber-lead, and iron fiber-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.

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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 utilized. Tests were conducted using specimens of tungsten fiber-copper, iron fiber-lead, and iron fiber-cadmium.

Room temperature tests were carried out on specimens of iron-lead and iron-cadmium to determine the variation of critical aspect ratio as a function of the interfiber distance. Reduction of the interfiber distance in the range 5 mils to 0.1 mil resulted in a decrease in the critical aspect ratio indicating a change in the apparent shear strength of the metal used to simulate the composite matrix. The apparent shear strength of lead was increased by 825 psi while the cadmium increased by 900 psi.

The effect of temperature was investigated using tungsten fiber-copper. Tests were conducted at temperatures up to 1500° F. For this system a rapid increase in the critical aspect ratio was noted for temperatures in excess of 1000° F although the data indicated that short length fibers (less than 1 in.) could be used to reinforce tungsten fiber-copper composites at a temperature equal to 0.8 of the melting point of copper.

INTRODUCTION

Fiber reinforced composites have received a good deal of attention in

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recent years because they offer the opportunity to provide structural members having unusually high 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.

Both theoretical (Ref. 1) and experimental (Ref. 2 and 3) investigations of such composites have been made. These early experimental results have shown that short length, discontinuous, fibers can be successfully utilized as reinforcement in composites. Also, it has been 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 termed the critical aspect ratio.

A direct way to approximate the critical aspect ratio is to vary the specimen geometry such that the failure mode is changed from "pull-out" of the fiber through shear failure of the matrix to tensile fracture of the fiber. Some work of this type has been done (Ref. 3) using wire embedded to varying depths in the matrix material. An additional investigation of the critical aspect ratio is warranted to explore variables for which little experimental data has been obtained. For example, the effect of separation distance between fibers on the critical aspect ratio has not been studied. It would be expected that 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 objectives of the present program were to determine the effect of temperature and interfiber distance on the critical aspect ratio utilizing model systems. Tungsten wire and iron wire were used as the fibers in this investigation while copper, lead, or cadmium was utilized as the matrix material. A specimen configuration designed to simulate conditions in a discontinuous fiber reinforced composite was used.

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

MATERIALS, APPARATUS AND PROCEDURE

Specimen Configuration

In composites containing discontinuous, uniaxially oriented fibers, figure 1(a), the 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 we tried to simulate the conditions occurring in a composite. In the figures, "L" and "l" refer to the length of the reinforcing fiber in the test specimen and in the composite, respectively. The length of the fiber in the test specimen "L" is equal to one-half the length of the fiber in an actual composite "l". 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 reminder of this report the aspect ratios (L/D) reported are those of the test specimen and must be increased by a factor of 2 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 drilled hole in the button and the distance between the fiber surface and the hole surface is essentially constant. In an actual composite, assuming fibers of a circular cross section, the interfiber distance varies. It is not clear what should be used as the effective interfiber distance. It is believed, however, that trends defined by the model will be helpful in understanding the behavior in a composite. For the present study the IFD's used were assumed to be the maximum IFD which would normally be encountered in most composites.

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 due to the very close fit of the fiber in the drilled hole, while alloying effects were minimized through the selection of suitable materials combinations. Cadmium and lead were used as infiltrants (matrix) because of their relative insolubility in iron which was used as the fiber. In addition they differ in crystal structure; lead being face centered cubic and cadmium being hexagonal close packed. Copper was used in combination with tungsten because of their mutual insolubility and also because a good deal of information on composites of this model system is available for comparison.

When mounted and tested in a fixture such as shown in figure 2, specimen failure would take place by either of two modes: shear failure in the infiltrant or at the interface (pull-out) or tensile failure of the wire. Specimens having an aspect ratio less than the critical aspect ratio would fail by pull-out while those having a aspect ratio greater than the critical aspect ratio would fail by tensile failure of the wire. Figure 3(a) shows a specimen prior to testing, while figure 3(b) shows a specimen which has failed by pull-out ($L/D < L_c/D$). Figure 3(c) shows a specimen which 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 7/16 inch rod to 0.0198±0.00005 inch diameter wire. After both the swaging and drawing operations the wire was annealed by heating to 1650° F in vacuum and furnace cooling.

Buttons were prepared by cutting lengths of the appropriate thickness from 7/16 inch diameter rod or by punching 7/16 inch diameter discs from ingot iron sheet which had been rolled to the required thickness. Both the cut and punched buttons were annealed in the same manner as the wire. This was done so that the properties of the wire and the button 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 jewelers lathe. Final hole size was obtained by using four flute, straight shank precision reamers to remove the final 0.0005 inch. 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. Using this drilling and reaming procedure it was possible to prepare holes of the required size with an accuracy of plus or minus 0.000035 inch. The thickness of the buttons was measured to the nearest 0.0001 inch using a precision micrometer. Using these techniques the accuracy of the L/D calculation of the specimens having an $L/D = 1$ was ± 0.005.

The buttons and wire were ultrasonically cleaned in acetone and given a light HCl 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, 1000° F, air atmosphere furnace, where they were heated for 5 minutes, removed and air cooled. Excess infiltrant was mechanically removed from the specimen prior to testing.

Ingot iron-cadmium. - Specimens of this combination were fabricated in the same manner as the ingot iron-lead specimens.

Tungsten-copper. - Tungsten buttons were fabricated by cold pressing 5 micron tungsten powder into discs of various thickness. These were drilled to the proper size so that after sintering for 4 hours at 4200° F, in vacuum, the button and hole had shrunk to the desired size, lengths of 0.010 inch diameter tungsten wire (type 218 CS) and a spiral of OFHC copper wire were assembled in the same manner as the iron-lead specimens and infiltrated in a hydrogen atmosphere for 15 minutes at 2200° F. Tests in this materials combination were limited to elevated temperature tests using a constant interfiber distance of 1.6 mils. This was because of the difficulty encountered in attempting to drill small holes of high precision in tungsten buttons. This became an even more difficult problem as the thickness of the button was increased. For this reason tests related to the interfiber distance effect were restricted to the more easily machined material as was described earlier.

Testing

Tests were conducted using an Instron tensile machine at a crosshead speed of 0.05 inch per minute. For the elevated temperature tests a furnace equipped with quartz heating lamps was used to heat the specimen. With such a heat source the specimens could be brought to test temperature very quickly. This, in addition to the flowing helium in the furnace, aided in minimizing oxidation during testing.

Shear strength of the cadmium, lead, and copper matrix materials in bulk form was determined using a double shear specimen and fixture such as is shown in figure 5. Tests were conducted at room temperature on these materials after they had been subjected to a thermal history which duplicated as much as possible, the thermal history of the infiltrant in the actual test specimen.

Deformation study. - In order to get an indication of the deformation taking place within a test specimen during loading, a series of special tests was run. Samples of ingot iron infiltrated with lead were photographed during testing. The buttons on the samples 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, figure 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 similar to that used for the regular tests except that the plated surface was exposed. Loading of the sample was carried out at room temperature in the tensile machine using a crosshead speed of 0.005 inch per minute 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 mm camera with a lens system which resulted in a 3X 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 Pull-Out Tests

Ingot iron-lead. - A summary of the results of this series of pull-out tests is given in table I, while 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 and 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 pull-out was taken as the critical aspect ratio. Values for the critical aspect ratio were arrived at by the intersection of the horizontal wire failure line with a line drawn from the origin to the point of last wire failure, i.e., wire failure for smallest aspect ratio.

Some specimens, shown on the figures as open symbols, particularly in those samples having very small IFD's failed by pull-out at values higher than the critical aspect ratio. These premature failures were the result of incomplete infiltration as shown by examination of wires which had pulled out. Without exception they showed areas on which there was no bond between the infiltrant and the wire. In addition, some wires broke at loads less than that which would normally be expected. These were probably due to welds in the wire. Welding of the wire during drawing was necessary in order that long lengths could be processed. Specimens 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 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 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. - Figures 8(a) to (f) show the results of tests conducted on iron wire infiltrated with cadmium. These tests were conducted over the same range of interfiber distances (0.1 mil to 5 mils) as the iron-lead specimens. At 0.1 mil (fig. 8(a)) the critical aspect ratio was 1.6 while at 0.2 mil (fig. 8(b)) interfiber distance it increased to 1.8 and at 0.5 mil (fig. 8(c)) to 1.9. At interfiber distances of 1, 2, and 5 mils (figs. 8(d) to (f)) the critical aspect ratio was constant at 1.9.

Tungsten-copper. - Results of the room temperature pull-out tests on specimens of tungsten wire and buttons infiltrated with 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 tungsten wire infiltrated with OFHC copper was 3.0 (IFD = 1.6 mils). The wire failure load shown is the average failure load for all samples which failed by tensile failure of the wire.

Elevated Temperature Tests

Figure 10 shows the results of elevated temperature tests conducted on specimens of 10 mil tungsten wire and pressed and sintered tungsten buttons infiltrated with OFHC copper (IFD = 1.6 mils). These results are also presented in table II.

Results of room temperature tests are included in figure 10. At 600° F the critical aspect ratio was found to have increased slightly to just over 3 while at 900° F it is somewhere between 3.9 and 4.7. At temperatures in excess of 900° F the change became much more rapid and at 1500° F 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 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). Further load, figure 11(c) causes deformation further along the wire. Figure 11(d) shows the section after failure of the lead has occurred and the wire has begun to pull out.

DISCUSSION

The determination of the critical aspect ratio in a discontinuous fiber reinforced composite is of extreme importance. It has a direct bearing on the limiting conditions under which such composites may be applied, particularly with respect to temperature. In addition, it determines the types of fibers which may be used as reinforcement. For example, in a case where very high strength fibers are available in only very short lengths the use of such fibers as reinforcement is limited by the number of suitable matrix materials of sufficiently high shear strength to accomplish load transfer.

The results of this investigation have shown that the critical aspect ratio is dependent upon the interfiber distance. This can be seen in figure 14 which is a summary plot of the critical aspect ratio as a function of interfiber distance for specimens of iron wire - lead and iron wire-cadmium. For the iron-lead specimens there is an 11 percent change in critical aspect ratio for distances from 5 mils to 0.5 mil. Between 0.5 mil and 0.2 mil the critical aspect ratio decreased 7 percent, from 5.6 to 5.1. When the lead thickness was reduced even further, to 0.1 mil the critical aspect ratio decreased an additional 8 percent, from 5.1 to 4.5. Tests conducted using iron wire and cadmium show a similar trend, figure 12 although not as pronounced as in the iron-lead specimens.

Another comparison of the effect of interfiber distance on the critical aspect ratio may be seen in figure 13. This figure shows a plot of the relative change, in percent, in the critical aspect ratio as a function of interfiber distance and was arrived at by taking the difference between the calculated critical aspect ratio and the observed critical aspect ratio. The calculated ratio was computed using the observed tensile strength of the wire and the shear strength obtained from bulk specimens of lead or cadmium tested separately (table III) in the relationship:

$$\left(\frac{L_c}{D}\right)_{calc} = \frac{1}{4}\frac{\sigma_w}{\tau_m}$$

where:

σ_w tensile failure strength of the wire

τ_m shear strength of the infiltrant tested externally

The observed critical aspect ratio was taken from the results of the pull-out tests.

Using the same relationship it was also possible to calculate the shear stress on the lead or cadmium for the specimens having the smallest aspect ratio which failed by tensile failure of the wire. This then is essentially the maximum shear stress to which the infiltrant was subjected during the test. The results of these calculations are plotted in figure 14 as a function of interfiber distance. These data show the same general trend seen in the plot of the relative change in critical aspect ratio as a function of interfiber distance, figure 13.

In the case of lead, the shear strength at an interfiber distance of 5 mils was about 10 percent greater than the shear strength of the bulk lead. As the interfiber distance was decreased to 2 mils the shear strength of the lead was nearly 22 percent greater than the bulk material. This trend continued until the interfiber distance was decreased to less than

0.5 mil where the shear strength increased much more rapidly. At an interfiber distance of 0.2 mil the increase was about 38 percent and at 0.1 mil the lead was nearly 57 percent stronger than the bulk lead.

Cadmium behaved in a manner similar to the lead. In the joints having thicknesses less than 0.5 mil the rapid increase in apparent shear strength was again noted. Since the number of operable slip systems in cadmium (close packed hexagonal) was less than in lead (face centered cubic) it would be expected that the cadmium would be more sensitive to triaxial strengthening. The difference in increased apparent shear strength was as expected, although quantitatively slight, with 900 psi for the cadmium and 826 psi for the 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 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 resulting in a joint of increased strength A more complete discussion of this phenomenon may be found in reference 6.

There are interesting features to be pointed out in the results of the deformation study on iron-lead specimens, figure 11. The first is that deformation across the lead from wire to button was not uniform, figures 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. In the case of this particular specimen the lead thickness was approximately 7 mils. The major portion of the deformation took place in the middle third of the thickness. This is shown by the "S" shape of the initially straight index marks, "A" in figure 11. Similar results have been observed in other systems (Ref. 7) and 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 and, as the total shear strain increased, 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. Correlation of the load-deformation curve with the photographs indicated that even after the specimen had been stressed to its highest stress level considerable 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, under certain special conditions, by allowing some fibers of less than critical aspect ratio to shear and pull out rather than fail in tension.

The increase in critical aspect ratio as a funtction of temperature, figure 10 is of importance because of the emphasis it places on the necessity of 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 fibers 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, fibers as short as 0.24 inch were sufficiently long to have failed in tension at a temperature equal to 0.8 of the melting point of the matrix. The use of a fiber 1 inch long would permit a discontinuous fiber composite utilizing about 90 percent of the full tensile strength of the fibers based on the relationship (Ref. 3) between fiber length and composite strength.

CONCLUDING REMARKS

The practical aspects of the results of this investigation bear some mention. Several investigators 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. These involve changing the shear properties of the matrix material since the only other 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 possibly 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 as a very thin film between two metals having a higher yield strength. Also, it was found by other investigators (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. Since 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 relationship between fiber content and tensile strength would be linear. At high fiber contents, depending upon 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 it would appear to be valid. Since 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.

While there are possible advantages to be obtained from achieving small interfiber distances there may be disadvantages as well. Little is known regarding the effect of temperature on triaxial strengthening. In addition it has been shown (Ref. 11) that the ductility of the composite may be adversely affected by very small interfiber distances.

Utilization of the "pull-out" method to determine the effect of interfiber distance and temperature on the critical aspect ratio has proven practical. However, this method has limitations. The values of critical aspect ratio can not be taken as absolute values in all cases. Under those conditions of materials system or temperature where work hardening of the matrix is not encountered this is not a problem. However, when appreciable work hardening is encountered in pull-out specimens 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 to 0.1 mil decreased the critical aspect ratio by 23 percent (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 structure) increased from 1450 psi when tested in the bulk form, 0.135 inch rod, to 2275 psi when tested as an infiltrant 0.1 mil thick. Under the same conditions cadmium (close packed hexagonal) shear strength increased from 5500 psi to 6400 psi.

3. Critical aspect ratio increased with decreasing matrix strength. For example, the critical aspect ratio of the copper-tungsten specimens increased rapidly, particularly at temperatures in excess of 1000° F. However, the critical aspect ratios obtained indicated that relatively short fibers could be used to reinforce copper at temperatures as high as 0.8 of the melting point of copper.

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TABLE I. - OBSERVED CRITICAL

ASPECT RATIO FOR VARIOUS WIRE

INFILTRANT COMBINATIONS

ROOM TEMPERATURE TESTS

Wire	Infiltrant	Interfiber distance (nominal), in.	Observed critical aspect ratio
Tungsten	Copper	0.0016	3.0
Ingot iron	Cadmium	.0001	1.6
		.0002	1.7
		.0005	1.8
		.001	1.9
		.002	1.9
		.005	1.8
	Lead	.0001	4.5
		.0002	5.1
		.0005	5.6
		.001	5.8
		.002	5.8
		.005	6.4

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

Interfiber distance (nominal), in.	Failure mode		Failure load, lb	Wire stress at failure	Aspect ratio	Test temperature, °F
	Wire	Pull-out				
0.0016		√	9.59	122,175	2.4	600
	√		13.27	169,050	3.4	
	√		13.34	169,950	4.5	
	√		13.56	172,750	5.6	
	√		13.60	173,250	3.8	
	√		11.53	146,875	4.8	900
	√		12.08	153,875	4.7	
		√	7.56	96,300	2.0	
		√	7.12	90,700	3.1	
		√	10.45	133,125	3.9	
	√		12.55	159,875	6.8	
	√		11.47	146 125	5.3	950
	√		10.45	133,125	6.5	1000
		√	9.77	124,450	4.9	1000
	√		10.69	136,175	7.0	1100
		√	9.44	120,250	5.2	1100
	√		10.01	127,525	6.4	1200
	√		10.30	131,200	8.9	1250
		√	10.14	129,175	6.3	1300
	√		9.24	117,700	13.6	1300
		√	9.37	119,250	8.5	1350
	√		9.53	121,400	8.6	1350
	√		9.72	123,825	8.6	1350
		√	8.62	109,800	6.2	1400
		√	8.42	107,250	13.8	1450
	√		5.67	72,225	24.9	1500
	√		2.18	27,775	15.3	1500
	√		8.95	114,000	15.4	1500

TABLE III. - SHEAR STRENGTH OF INFILTRANT METALS - BULK SPECIMENS

Metal	Condition	Test temperature, °F	Shear strength (average of 5 tests), psi
Lead	Chill cast	RT	1,450
Cadmium	Chill cast	RT	5,500
Copper	Annealed 1 hr at 1500° F	RT	20,600
↓	↓	300	17,150
↓	↓	600	12,500
↓	↓	900	8,150
↓	↓	1200	3,400
↓	↓	1500	350

E-4154

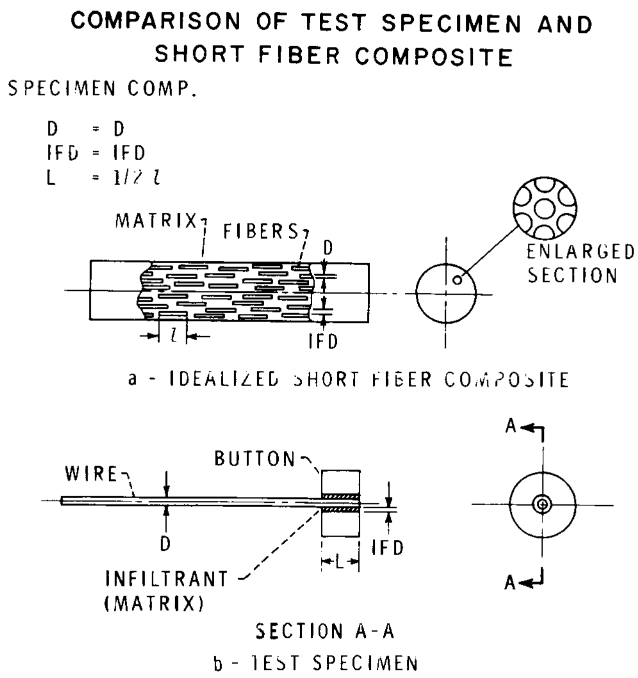


Figure 1

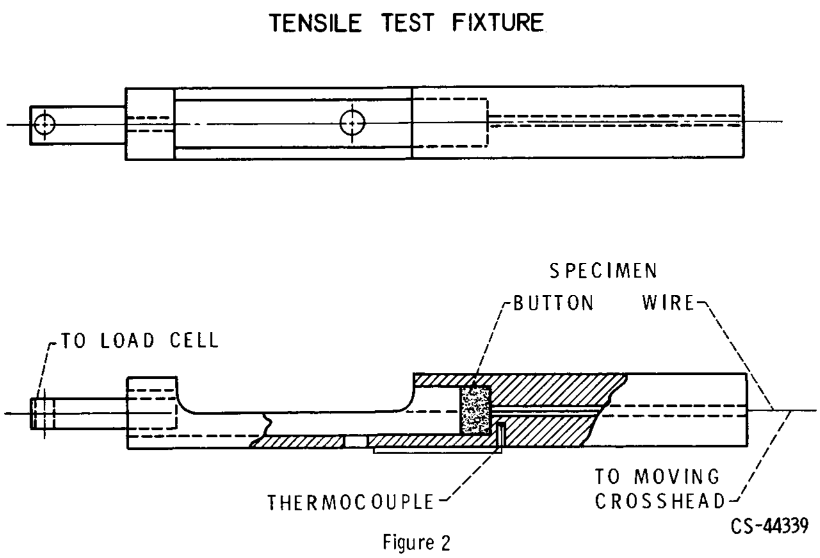
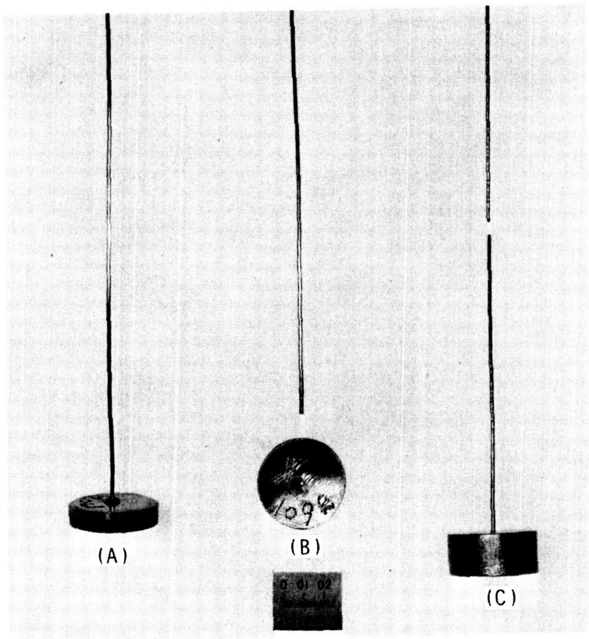


Figure 2

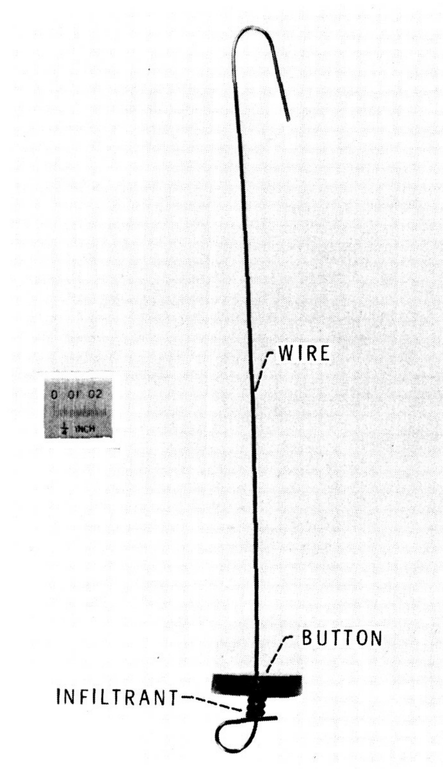
ASPECT RATIO TEST SPECIMENS



(A) BEFORE TESTING, (B) PULLOUT FAILURE, (C) WIRE FAILURE.
CS-44332

Figure 3

ASPECT RATIO TEST SPECIMEN PRIOR TO INFILTRATION



CS-44331

Figure 4

E-4154

SHEAR TEST FIXTURE

DOUBLE SHEAR

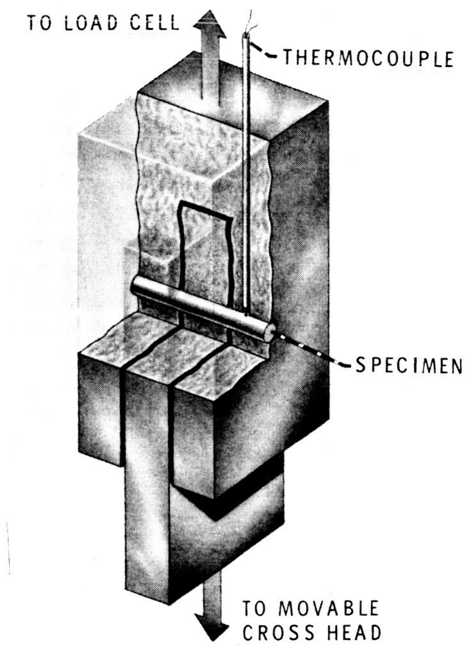


Figure 5

DEFORMATION STUDY SPECIMEN

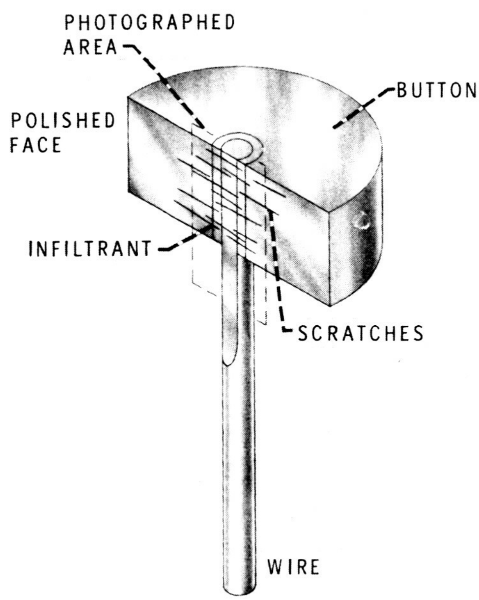


Figure 6

E-4154

FAILURE LOAD AND MODE AT VARIOUS ASPECT RATIOS

INGOT IRON-LEAD, ROOM TEMP
INTERFIBER DISTANCE, 0.1 MIL

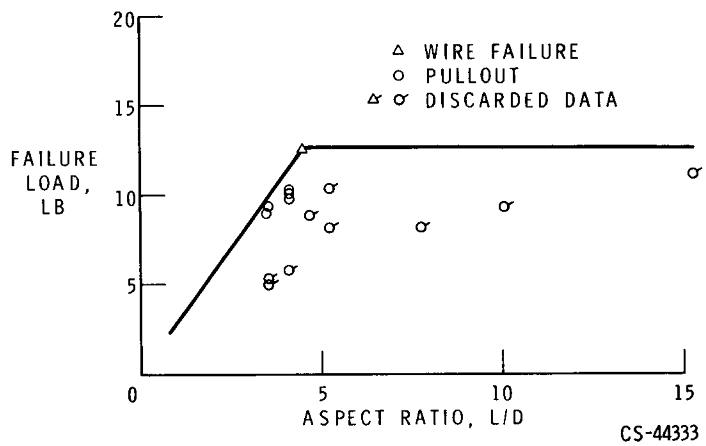


Figure 7(a)

FAILURE LOAD AND MODE AT VARIOUS ASPECT RATIOS

INGOT IRON-LEAD, ROOM TEMP
INTERFIBER DISTANCE, 0.2 MIL

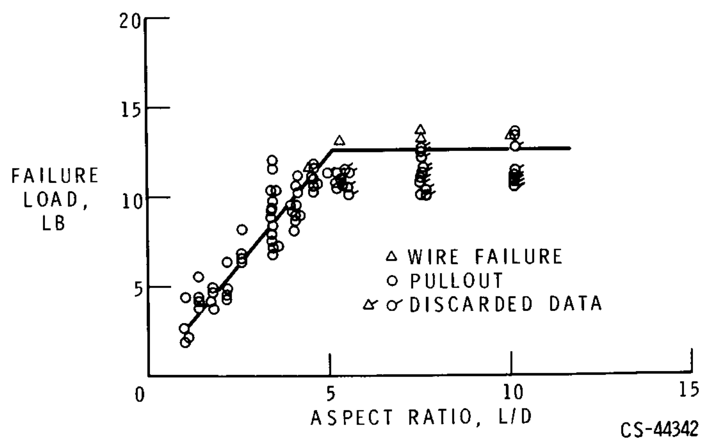


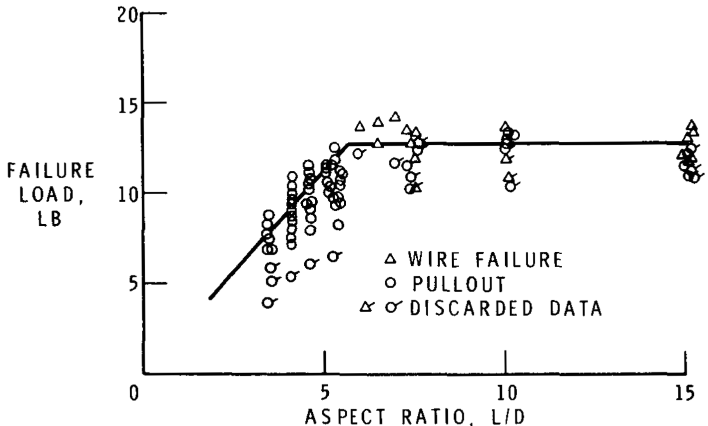
Figure 7(b)

E-4154

FAILURE LOAD AND MODE AT VARIOUS ASPECT RATIOS

INGOT IRON-LEAD, ROOM TEMP

INTERFIBER DISTANCE, 0.5 MIL



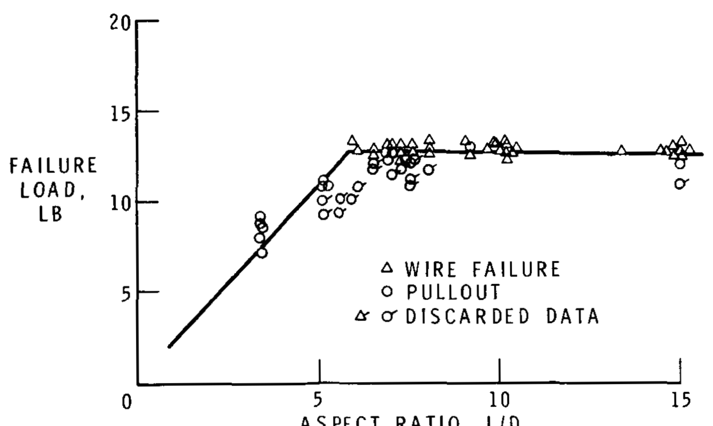
CS-44344

Figure 7(c)

FAILURE LOAD AND MODE AT VARIOUS ASPECT RATIOS

INGOT IRON-LEAD, ROOM TEMP

INTERFIBER DISTANCE, 1.0 MIL



CS-44341

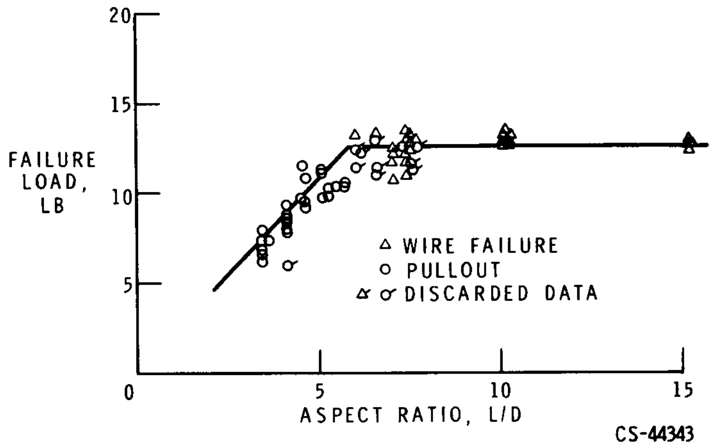
Figure 7(d)

E-4154

FAILURE LOAD AND MORE AT VARIOUS ASPECT RATIOS

INGOT IRON-LEAD, ROOM TEMP

INTERFIBER DISTANCE, 2.0 MILS



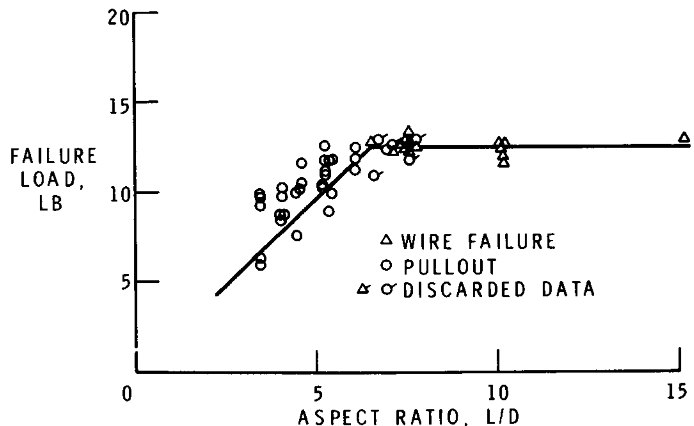
CS-44343

Figure 7(e)

FAILURE LOAD AND MODE AT VARIOUS ASPECT RATIOS

INGOT IRON-LEAD, ROOM TEMP

INTERFIBER DISTANCE, 5 MILS



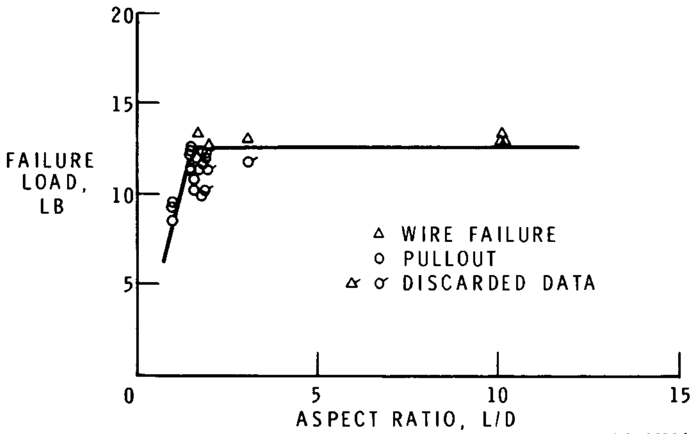
CS-44345

Figure 7(f)

E-4154

FAILURE LOAD AND MODE AT VARIOUS ASPECT RATIOS

INGOT IRON-CADMIUM, ROOM TEMP
INTERFIBER DISTANCE, 0.1 MIL

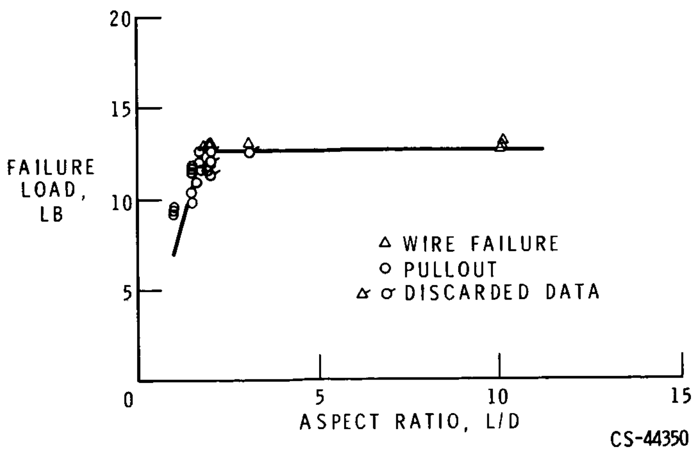


CS-44334

Figure 8(a)

FAILURE LOAD AND MODE AT VARIOUS ASPECT RATIOS

INGOT IRON-CADMIUM, ROOM TEMP
INTERFIBER DISTANCE, 0.2 MIL



CS-44350

Figure 8(b)

E-4154

FAILURE LOAD AND MODE AT VARIOUS ASPECT RATIOS

INGOT IRON-CADMIUM, ROOM TEMP
INTERFIBER DISTANCE, 0.5 MIL

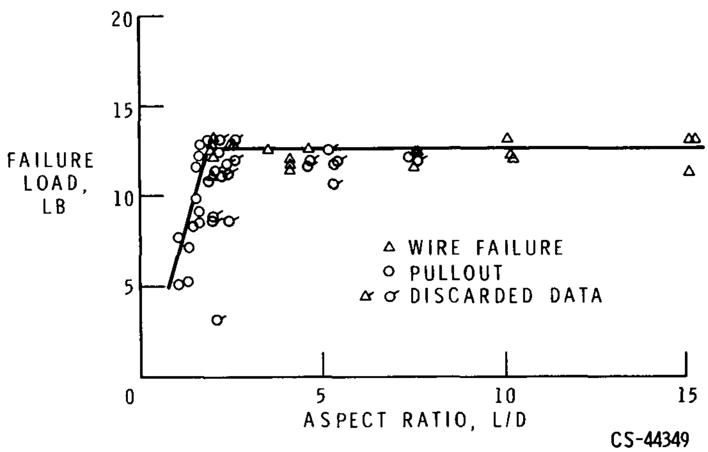


Figure 8(c)

FAILURE LOAD AND MODE AT VARIOUS ASPECT RATIOS

INGOT IRON-CADMIUM, ROOM TEMP
INTERFIBER DISTANCE, 1 MIL

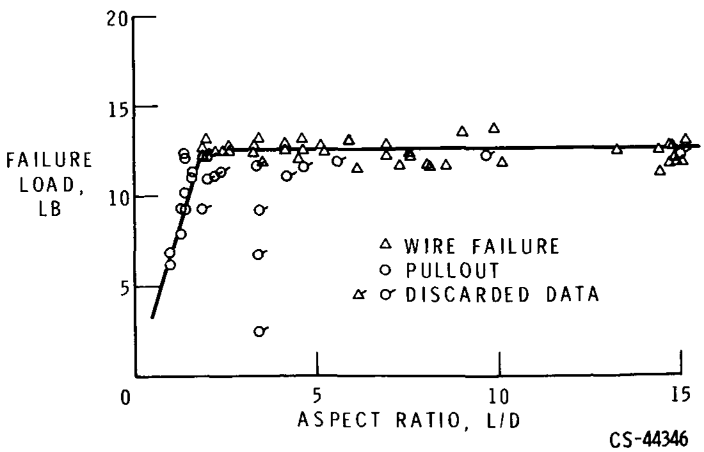


Figure 8(d)

FAILURE LOAD AND MODE AT VARIOUS ASPECT RATIOS

INGOT IRON-CADMIUM, ROOM TEMP
INTERFIBER DISTANCE, 2 MILS

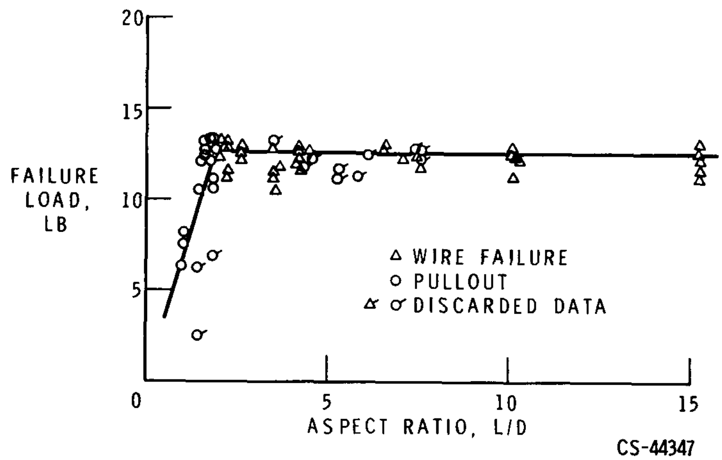


Figure 8(e)

FAILURE LOAD AND MODE AT VARIOUS ASPECT RATIOS

INGOT IRON-CADMIUM, ROOM TEMP
INTERFIBER DISTANCE, 5 MILS

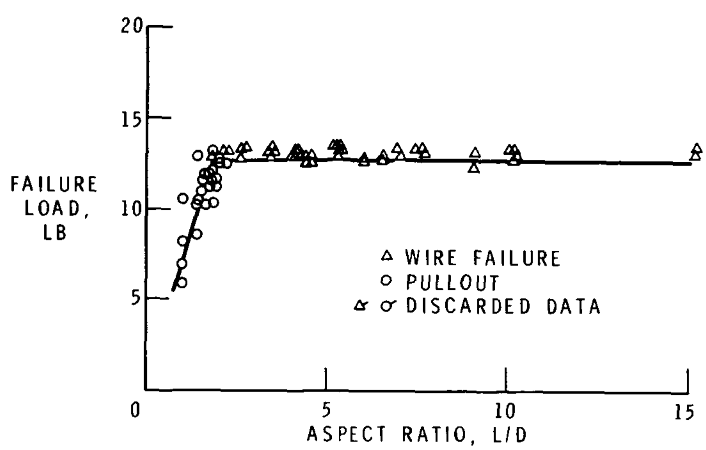


Figure 8(f)

E-4154

FAILURE LOAD AND MODE AT VARIOUS ASPECT RATIOS

TUNGSTEN WIRE-COPPER, ROOM TEMP
INTERFIBER DISTANCE, 1.6 MILS

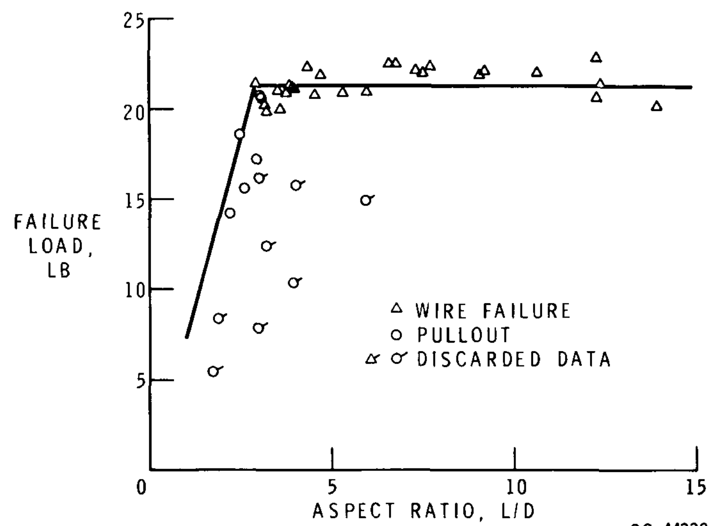


Figure 9

CRITICAL ASPECT RATIO AS A FUNCTION OF TEMPERATURE

TUNGSTEN WIRE-COPPER, INTERFIBER DISTANCE, 1.6 MILS

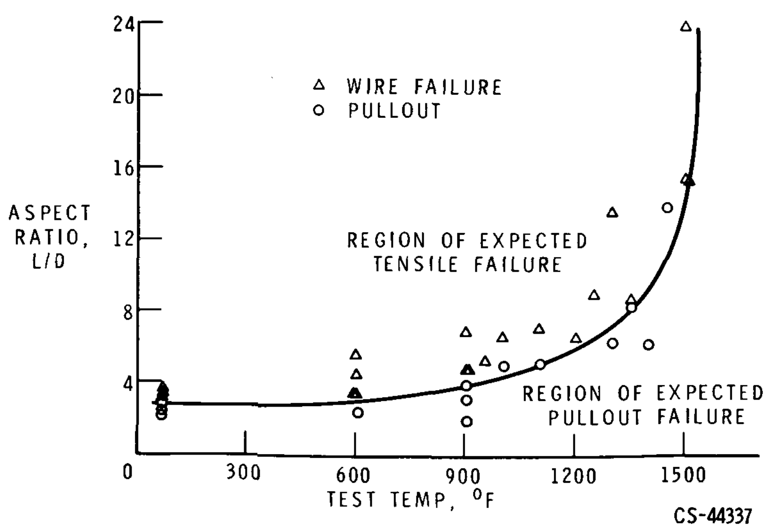
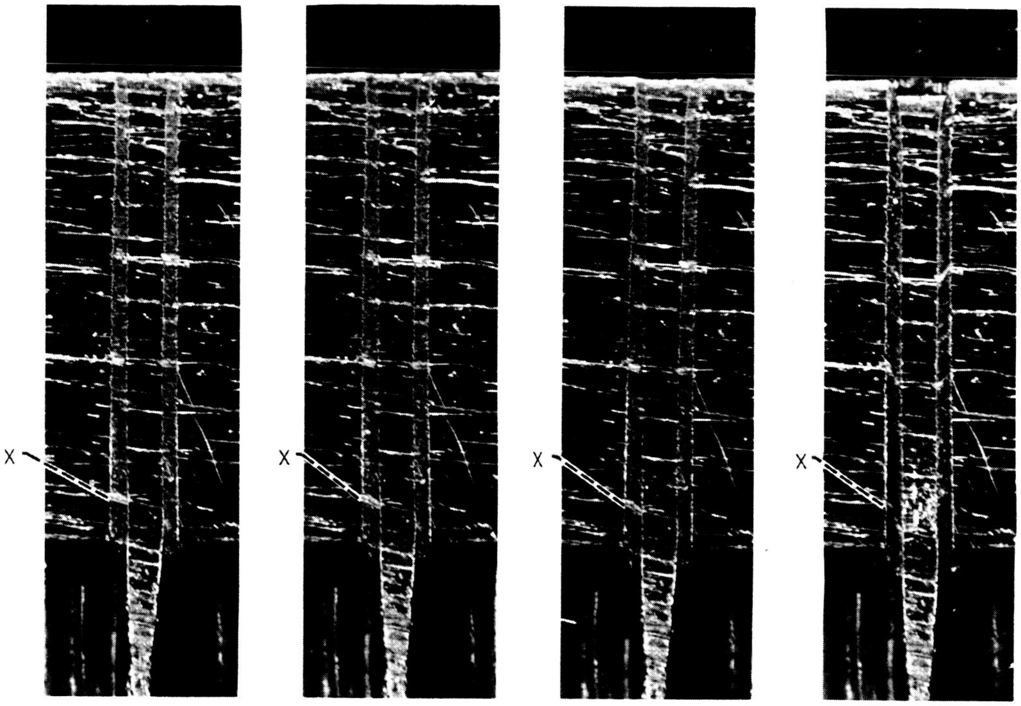


Figure 10

E-4154

SEQUENTIAL PHOTOGRAPHS OF DEFORMATION TESTS

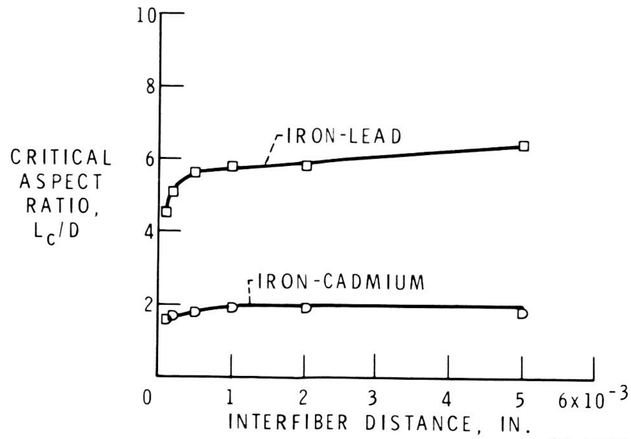


(A) NO LOAD. (B) LOW LOAD. (C) MEDIUM LOAD. (D) PULLOUT.
X (INDEX MARK).

CS-44390

Figure 11

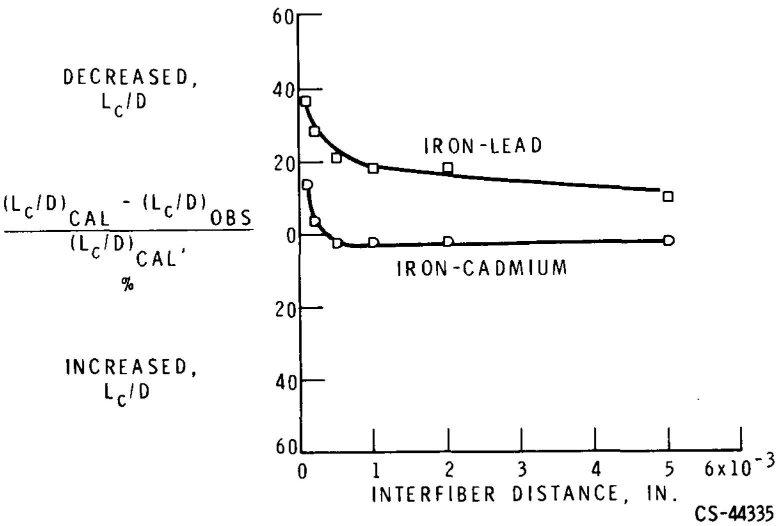
OBSERVED CRITICAL ASPECT RATIO
AT VARIOUS INTERFIBER DISTANCES



CS-44336

Figure 12

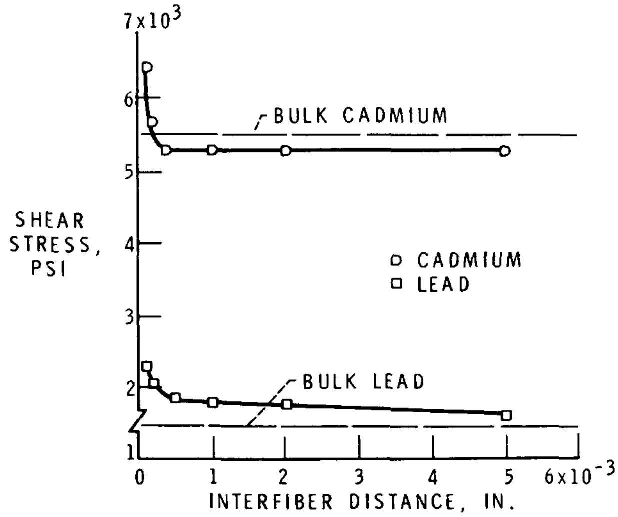
CHANGE IN CRITICAL ASPECT RATIO AS A FUNCTION OF INTERFIBER DISTANCE



CS-44335

Figure 13

SHEAR STRESS ON INFILTRANT AT VARIOUS INTERFIBER DISTANCES



CS-44340

Figure 14