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TENSILE BEHAVIOR OF UNNOTCHED AND NOTCHED TUNGSTEN-COPPER LAMINAR COMPOSITES

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16. Abstract

A study was conducted to determine the relations between the tensile strengths of unnotched and of notched, and elastic moduli of unnotched laminar sheet or foil composites and the amounts of reinforcement. Tungsten was used as the reinforcement and copper as the matrix and the tests were run at room temperature. Three thicknesses of tungsten (i.e., 0.00254, 0.0127, and 0.0254 cm (0.001, 0.005, and 0.010 in.)) were used and the nominal volume fraction of tungsten was varied from about 0.05 to 0.95. It was found that the tensile strength of the unnotched specimens could be related to the amount of reinforcement, as could the elastic moduli, and that these values could be predicted by use of the rule of mixtures. The tensile strengths of the notched laminar composites could be predicted by use of the rule of mixtures using strengths for notched constituents, provided notch effects did not predominate.

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TENSILE BEHAVIOR OF UNNOTCHED AND NOTCHED TUNGSTEN-COPPER LAMINAR COMPOSITES

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SUMMARY

A study was conducted of multilayered laminar composites composed of integrally bonded sheets of the mutually insoluble materials - tungsten and copper. Specific objectives were to determine relations of the composite mechanical properties to constituent mechanical properties and to the quantities and thicknesses of the reinforcing constituents. Both notched and unnotched composites were to be studied. Three thicknesses of tungsten sheet were used as reinforcements, namely, 0.00254, 0.0127, and 0.0254 cm (0.001, 0.005, and 0.010 in.). Nominal volume fractions of tungsten in composites were varied from 0.05 to 0.95.

It was found that the ultimate tensile strengths of the unnotched composites closely approached rule-of-mixtures values calculated using the average ultimate tensile strengths of copper and tungsten sheet (tested separately) in an appropriate equation. Elastic moduli of unnotched laminar composites were also close to calculated rule-of-mixtures values. In these respects laminar composites were found to be similar in behavior to fiber composites.

Notched composites came close to "obeying" the rule-of-mixtures relation over a range of reinforcement contents extending from 0.05 to 0.60 or 0.80 volume fraction (v/f) of tungsten. For the notch geometry used, about two-thirds of all specimens tested had notched to unnotched strength ratios of 0.8 or more. The composites with the thickest tungsten reinforcing laminae were for the most part, notch strengthened, that is, they had notched to unnotched strength ratios of 1.0 or more. The notched composites containing the 0.0127- and 0.0254-cm- (0.005- and 0.010-in. -) thick tungsten reinforcing laminae exhibited a dropoff in strength at high volume fractions of reinforcing laminae (above 0.6 to 0.8 v/f, respectively) and did not "obey" the rule of mixtures.

INTRODUCTION

Laminar composites composed of bonded layers of sheet or foil of different metals or alloys are expected to evolve into useful engineering materials. They have potential for aerospace power systems, and structural applications for which high strength-to-weight and modulus-to-weight ratio and higher use temperature materials are constantly being sought. Components for powerplants such as turbine disks, blades, vanes, and shafts might readily be made from sheet or foil laminar composites. Higher use temperature materials would permit operation of aircraft gas turbines and other powerplants at higher temperatures, thereby increasing their efficiency and, in some instances, simultaneously lowering polluting emissions.

Very high strengths are obtainable from thin metallic film and from some foil materials (refs. 1, 2, and 3). Relatively recent attempts have been made to make integrally bonded, multilayered, laminar composites using high strength thin sheets or foils for reinforcement along with weaker, more ductile, and/or more corrosion resistant materials for matrices (refs. 4 to 8). Some of the property advantages of such composites relative to conventional materials that have been reported are: Improved impact resistance (refs. 5 and 6), bending characteristics (ref. 7), tensile strengths (ref. 6), high temperature tensile strengths (ref. 8), and stress-rupture strengths (refs. 7 and 8). However, none of the references cited included a systematic study of any of the aforementioned properties as a function of the variable, reinforcement content. In fact, in the previous studies, only a single volume fraction of reinforcement was used for each material combination. Finally, most of the composites of references 5 to 8 were composed of mutually reactive materials and thus the results may have been affected to varying degrees by metallurgical factors.

To understand the fundamental strengthening mechanisms associated with most types of composites, reactivity between reinforcement and matrix must be eliminated as a variable. Model systems comprised of mutually insoluble materials should be selected to avoid such reactions. In addition, a model system should consist of reinforcement and matrix materials which have mechanical and physical properties at least somewhat representative of materials that are likely to be used in practical composites. Tungsten and copper were selected for this study because they fulfill the aforementioned requirements. Tungsten is strong and brittle at ambient temperatures and has a high modulus of elasticity and a low coefficient of thermal expansion. Copper is relatively weak and ductile and has a low modulus of elasticity and a high coefficient of thermal expansion. Metal composites having constituents with properties similar to those of tungsten and copper should behave similarly to tungsten/copper composites. Similarity of behavior will be expected if the composite constituents which are used can be prevented from reacting deleteriously during fabrication or during use.

In view of the potential of laminar composites and the need for a systematic study of the relation of the mechanical properties of such composites and the mechanical properties as well as quantities and thicknesses of constituents comprising the composites, a model system study of multilayered tungsten/copper laminar composites was undertaken.

Laminar composites were made having nominal volume fractions (v/f) of tungsten ranging from 0.05 to 0.95. Three thicknesses of tungsten sheet, that is, 0.00254, 0.0127, and 0.0254 cm (0.001, 0.005, and 0.010 in.) and 12 thicknesses of copper ranging from 0.00038 to 0.2413 cm (0.00015 to 0.095 in.) were used. To produce composites of different volume fractions of tungsten for a given thickness of tungsten, it was necessary to use different thicknesses of copper between the tungsten layers. The specimens were made by mechanical hot pressing.

Room temperature tensile tests were made with unnotched and notched laminar composite specimens. Tungsten and copper lamina, unnotched and notched, were also tested in tension at room temperature. Load-strain data were obtained for unnotched laminar composites. The effect of reinforcement orientation was not studied; it was expected to be slight.

MATERIALS, APPARATUS AND PROCEDURE

Sheet Materials

Tungsten and copper sheet were obtained from commercial sources. The chemical analyses furnished by the suppliers are given in table I. The tungsten was obtained from a single lot of powder and the copper was obtained from a single melt of material. The tungsten was obtained in three thicknesses, that is, 0.00254, 0.0127, and 0.0254 cm (0.001, 0.005, and 0.010 in.). Twelve thicknesses of copper, ranging from 0.000381 to 0.2413 cm (0.00015 to 0.95 in.) were used. The tungsten was obtained in the as-rolled condition and the copper was fully annealed.

Apparatus

A vacuum hot press having capacities of 1704° C (2100° F), 5.5- kN/cm^2 (8-ksi) ram stress, and 13.3-MN/cm^3 (10^{-3}-torr) vacuum level was used to consolidate the composite specimens. An 89-kN (20-000 lb) rated, screw driven tensile test machine having a 44.5-kN (10 000-lb) capacity load cell and a hydraulic tensile test machine having a load capacity of 111.2 kN (25 000 lb) were used.

Procedure

Sheet and laminar composite specimens. - Sketches of unnotched and notched sheet and composite specimens are shown in figures 1 and 2. All specimens were made with the original sheet rolling direction alined parallel to their tensile axes. The nominal theoretical stress concentration factor K_t for the notched specimens was 5.8, a value determined using tables in reference 9. Tensile specimens of tungsten and copper lamina were made by stacking layers of sheet between two steel plates, clamping the assembly and then grinding to obtain the desired configuration. Notches were contour ground to radii of 0.0127 to 0.0254 cm (0.005 to 0.010 in.). The pin holes were electrical discharge machined in the tungsten lamina and drilled in the copper lamina.

The laminar composite specimens were made by stacking alternate layers (2.54 by 10.16 cm or 1 by 4 in.) of copper and tungsten and then hot pressing the stacks for 4 hours in the vacuum hot press apparatus. The pressure used was 1.4 kN/cm^2 (2 ksi), and the stacks were held at a temperature of 982° C (1800° F) for 4 hours. More specific details are presented in reference 8. The laminar composite tensile specimens were individually ground to shape and the pin holes were made using electrical discharge machining. The position of the notches in the notched specimens is shown in figure 2.

Composite specimens had either 0.00254-, 0.0127-, or 0.0254-cm- (0.001-, 0.005-, or 0.010-in.-) thick tungsten laminae. Copper laminae of thicknesses ranging between 0.000381 to 0.2413 cm (0.00015 to 0.095 in.) were used to obtain nominal volume fractions of reinforcement in the composites ranging from 0.05 to 0.95. The constitution (i.e., thickness, numbers, and volume fraction (v/f) of the laminae) of the various specimens tested are indicated in table II. Initially composite specimens were made to a thickness of approximately 0.508 cm (0.20 in.). Later composite specimens were made approximately 0.254 cm (0.10 in.) thick and had narrower test sections. The latter specimens were made to conserve material and to reduce tensile machine loads.

Metallographic examination of specimens after tensile testing indicated that the laminae within the composites were of the same nominal thickness as in the starting materials. The volume fraction of constituent in each composite specimen was based upon the nominal thicknesses of the starting materials.

Tensile tests. - Prior to tensile testing, the tungsten and copper lamina sheet specimens were given a 4-hour heat treatment at 982° C (1800° F) in vacuum to simulate the thermal and environmental exposure given to the laminar composite specimens during consolidation. Tensile tests were conducted at room temperature, using a crosshead speed of 0.127 cm/min (0.05 in./min). Load elongation curves were obtained for each tensile test. Four thicknesses, that is, 0.00381, 0.01651, 0.03302, and 0.2413 cm (0.0015, 0.0065, 0.013, and 0.095 in.) of copper foil or sheet were tensile tested. Tungsten of all three thicknesses was tested, and all of the laminar composite combinations were tested. Protective constraining devices were attached to some of the

0.00254- and 0.0127-cm- (0.001- and 0.005-in.-) thick tungsten lamina specimens (fig. 3) to prevent bending or twisting while being handled.

Elongation measurements. - Elongation at fracture was estimated from load-crosshead displacement curves for all composite specimens and for some sheet specimens tested in tension.

Load-strain tests for elastic moduli determinations. - Longitudinal strain of composite specimens was measured by using temperature compensated electrical resistance strain gages. The specimens were strained to approximately 0.25 percent. Gages were attached to both sides of the specimens, and load-strain curves (on both load and unload cycles) were obtained using a screw driven 89-kN (20 000-lb) capacity tensile machine and an x-y (load-strain) recorder. The strain rate was about 0.10 cm/min (0.04 in./min). These tests were performed at a commercial testing laboratory.

Metallographic studies. - All laminar composite specimens and selected sheet specimens were metallographically studied after fracture. The longitudinal edge at or near the fracture was examined.

RESULTS

Tensile Tests of Notched and Unnotched Tungsten and Copper Sheet Laminae

Unnotched tungsten. - The results of the tensile tests on the tungsten laminae are summarized in table III and plotted in figure 4 (at a v/f of 1.0). The average tensile strengths of the laminae were 179.0, 148.2, and 125.0 kN/cm^2 (260.0, 214.8, and 181.4 ksi) for thicknesses of 0.00254, 0.0127, and 0.0254 cm (0.001, 0.005, and 0.010 in.), respectively. The standard deviations were 29.1, 23.5, and 5.2 kN/cm^2 (42.5, 34.1, and 7.5 ksi), respectively. Average tensile strengths of the tungsten laminae were inversely related to thickness. Specimens exhibited essentially zero elongation at fracture.

Notched tungsten. - The tensile strengths for notched tungsten specimens are also given in table III; the average values were as follows: 131.4, 164.7, and 156.1 kN/cm^2 (190.7, 239.0, and 226.5 ksi) for laminae having thicknesses of 0.00254, 0.0127, and 0.0254 cm (0.001, 0.005, and 0.010 in.), respectively. The corresponding standard deviations were 33.8, 22.9, and 42.3 kN/cm^2 (49.1, 33.2, and 61.4 ksi). The fractured specimens exhibited essentially zero elongation. The 0.0127- and 0.0254-cm- (0.005- and 0.010-in.-) thick notched sheet specimens had average tensile strengths greater than unnotched specimens, while the average tensile strength for the 0.00254-cm- (0.001-in.-) thick notched specimens was less than for unnotched specimens.

Unnotched copper. - Average tensile strengths were obtained for four of the twelve lamina thicknesses used for the composites. Specimens tested had the following thicknesses: 0.00381, 0.01651, 0.03312, and 0.2413 cm (0.0015, 0.0065, 0.013, and 0.095 in.).

Average tensile strengths ranged from 13.0 to 17.3 kN/cm^2 (18.8 to 25.1 ksi) (table IV) and the average strength of all specimens was 15.1 kN/cm^2 (21.9 ksi). This value of average strength was plotted in all graphs of figure 4 at a tungsten v/f of zero to represent the strength of copper. Elongation at fracture for individual specimens ranged from 8 percent for the 0.00381-cm- (0.0015-in.-) thick lamina to 56 percent for the 0.2413-cm- (0.095-in.-) thick lamina (table IV).

Notched copper. - The data for notched copper lamina are also given in table IV. The thinner laminae, that is, those measuring 0.00381, 0.01651, and 0.03312 cm (0.0015, 0.0065, and 0.013 in.) were notch weakened, while the 0.2413-cm- (0.095-in.-) thick laminae were notch strengthened. The average notched tensile strength was 13.0 kN/cm^2 (18.9 ksi), for the four thicknesses. Elongations of individual specimens at failure ranged from 8 to 38 percent. Notched laminae in all but one case, exhibited less elongation at fracture than did the unnotched laminae of comparable thickness (table IV).

Tensile Tests of Composites

Unnotched specimens. - The tensile test results obtained for the unnotched laminar composites are given in table V. These data along with rectilinear least-mean-square (LMS) lines representing composite data are plotted in figure 4. Note that the data exhibit very little scatter and that data points fall very close to the LMS line. Straight rule-of-mixture (ROM) lines are also shown in this figure. Values used to plot the ROM lines were calculated using the average tensile strengths of tungsten laminae of a given thickness (table III) and from the overall average tensile strengths obtained for all copper laminae tested (table IV).

Notched specimens. - The strength-volume fraction reinforcement data for notched composites are also presented in table V and plotted in figure 5. The relation for the composite series reinforced with 0.00254-cm- (0.001-in.-) thick tungsten laminae appears linear over the entire composition range. However, the composites containing 0.78 or 0.91 v/f tungsten reinforcement and represented by symbols having upward-pointing arrows failed at the pin holes. The strength-volume fraction reinforcement relations for the composites containing 0.0127- or 0.0254-cm- (0.005- and 0.010-in.-) thick tungsten were linear up to about 0.60 v/f for the composites containing 0.0127-cm- (0.005-in.-) tungsten and to about 0.80 v/f for composites containing 0.0254-cm- (0.010-in.-) thick tungsten reinforcement; above these values, the strengths of the composites dropped off (figs. 5(b) and (c)). Straight LMS lines were fitted to the data up to a nominal volume fraction of 0.60 for the composites containing the 0.00254- and 0.0127-cm- (0.001- and 0.005-in.-) thick tungsten laminae (figs. 5(a) and (b)), and up to 0.80

for the composites containing the 0.0254-cm- (0.010-in.-) thick tungsten laminae (fig. 5(c)). Beyond the aforementioned volume fractions, curves were faired in. Straight ROM lines are drawn in figures 5(a) to (c) and are based on overall average notched copper lamina ultimate tensile strengths (i.e., for the four thicknesses tested, table IV) and the average notch strength value for the corresponding thickness of tungsten used (table III).

Elongation of fractured unnotched and notched laminar composite specimens. - Unnotched composites with low volume fractions of reinforcement, exhibited appreciable elongation (table V). Composites with a volume fraction of about 0.05 exhibited 12 to 28 percent elongation and composites with a volume fraction of about 0.20, exhibited up to 9 percent elongation. No elongation was measurable for fractured unnotched specimens with more than 0.20 v/f tungsten. Notched specimens containing about 0.05 v/f tungsten reinforcement exhibited 5 to 9 percent elongation. However, there was no observable elongation for fractured notched specimens containing more than 0.05 v/f reinforcement.

Stress-strain results and Young's modulus for unnotched laminar composites. - Typical load-strain curves for unnotched composites are presented in figure 6. Both curves represent composites containing 0.00254-cm- (0.001-in.-) thick tungsten laminae. The deviation from linearity (fig. 6(a)) presumably indicates yielding of the matrix and was found in all specimens having 0.80 v/f of reinforcement or less. The specimens with a very high (e.g., 0.91 v/f) reinforcement provided substantially straight lines (fig. 6(b)). The strains at which a departure from a linear relation occurred increased as the v/f of tungsten reinforcement was increased.

Modulus of elasticity values were calculated from the straight line portions of the load-strain curves (corresponding to regions A and B of fig. 6(a)) and are plotted in figure 7 and presented in table VI. The data were obtained for the 0.254-cm- (0.10-in.-) thick composite specimens only. A straight LMS line was fitted to the data (fig. 7).

Metallographic Results

Photomicrographs of typical fractured composite specimens are shown in figures 8 to 10. The tungsten failed in a brittle manner in all composites. In the low v/f tungsten composites, the copper always failed in a ductile manner by necking down. In addition to the prime fracture, smaller cracks occurred near the fracture surface in all specimens examined. In some areas the cracks progressed through both tungsten and copper laminae, and in other areas cracks occurred only in the tungsten while leaving the intervening copper intact. Vertical splitting of the bonds between the tungsten and copper or splitting of the tungsten was noted in specimens with a high v/f of 0.00254-cm- (0.001-in.-) thick tungsten.

DISCUSSION

Tensile Behavior of Unnotched Composites

To determine the effectiveness of reinforcements in composites, individual experimental tensile strengths of composites (or curves representing composite data) may be compared with ROM calculated strengths of composites or constructed ROM lines. Rule-of-mixture relations were calculated using tensile strengths of individually tested tungsten and copper sheet specimens. A plot of these calculations is a straight line connecting the average strengths of the constituents. When experimental data are close to the ROM line, the composites may be said to "obey" the ROM relation.

When a composite "obeys" the ROM relation, each constituent of the composite contributes its full share of strength in direct relation to the volume percentage or fraction of the constituent (refs. 10 and 11). Also, if a composite obeys the ROM relation, an equation representing the ROM relation can be used to predict composite strengths if the strengths of the constituents that comprise the composite are known.

Figure 4 indicates that the ROM and LMS lines for the composites with the 0.0127- and 0.0254-cm- (0.005- and 0.010-in.-) thick tungsten laminae are in very good agreement while the lines for the composites with the 0.00254-cm- (0.001-in.-) thick tungsten laminae are in fair agreement. In the latter case, the composite strengths were only about 10 percent under ROM values at large amounts of reinforcements. The average measured strengths of the two thicker groups of tungsten sheet were close to, but somewhat greater, than the values for tungsten laminae obtained by extrapolating composite data via the LMS curves. But the average measured strength of the 0.00254-cm- (0.001-in.-) thick tungsten sheet was appreciably greater than that for tungsten laminae obtained by extrapolating composite data via the LMS curve (table VII).

The unnotched strengths of the laminar composites followed the same trend as that of the tungsten laminae of various thicknesses; namely, composite strengths tended to decrease with increasing thickness of the tungsten laminae within the composite. Strength of sheet usually increases as thickness is decreased by mechanical working (rolling). The aforementioned relation, however, is believed to be related solely to the strength of the laminae.

The LMS equations for unnotched copper composite data, yielded the values for copper strength indicated in table VII, the average strength being 15.4 kN/cm^2 (22.3 ksi). This was close to the average strength of 15.1 kN/cm^2 (21.9 ksi) for four thicknesses of unnotched copper laminae tested separately (table IV). An average strength value was used for the copper laminae because it was necessary to vary the interlayer thickness of copper in composites as the volume fraction of the tungsten was varied. The individual values calculated for copper for the different composites were close to or slightly above the average measured strengths of the copper sheet (table VII).

The comparisons made previously indicate that the copper laminae within the composites achieved their full ultimate tensile strength capability. This is a different behavior from that observed for the tungsten fiber/copper matrix model system composites of references 10 and 11, where it was shown that the full benefit of the copper matrix ultimate tensile strength was not realized in the composites. In fact, in references 10 and 11, the copper matrices were shown to sustain a stress of only about one-fourth that of the ultimate tensile strength of copper. In reference 12, an equation was derived that indicates that it is necessary to add reinforcements to fiber composites in excess of a "critical volume fraction" in order to achieve composite strengths greater than the ultimate tensile strength of the matrix alone. Since the present investigation has shown that the full strength of the matrix was utilized in all v/f values of reinforcements, it may be assumed that any addition of reinforcing laminae to a ductile matrix would cause strengthening in a laminar composite. Fiber composites with reinforcements approximately as strong as the tungsten sheet laminae of this study (e.g., the 0.00254-cm- or 0.001-in.-thick tungsten), on the other hand, would require an addition of an appreciable quantity of fibers (approximately 9 percent) to produce a composite with a strength greater than that of the matrix alone. From the data obtained in this investigation, it can be concluded that the following ROM equation closely represents strengths for the unnotched composites of this investigation:

$$\sigma_c = \sigma_r v_r + \sigma_m v_m \tag{1}$$

where

σ_c ultimate tensile strength of (UTS) composite

σ_r average UTS of reinforcing or strong laminae[1]

v_r volume fraction of reinforcement laminae

σ_m average UTS of matrix laminae[1]

v_m volume fraction of matrix laminae

Elastic Moduli of Unnotched Composites

Elastic moduli of laminar composites and corresponding volume fractions of reinforcement have been plotted in figure 7 as already indicated. A LMS straight line was fitted to the data. No pronounced effects of reinforcing laminae thickness on moduli of composites are indicated by the figure. It appears, however, that most of the

[1]Laminae were heat treated to simulate thermal treatment used in hot pressing composites.

composites with the thinnest tungsten laminae had greater moduli than did the other composites. Solution of the LMS equation gave elastic moduli of 11.4 MN/cm^2 (16.6 Mpsi) for copper and 40.3 MN/cm^2 (58 Mpsi) for tungsten. These values for the copper and tungsten are in good agreement with published values of 13.0 MN/cm^2 (18.7 Mpsi) for copper and 40.0 MN/cm^2 (60.4 Mpsi) for tungsten (ref. 13). Thus the elastic moduli of the composites of this study may be represented by a ROM equation, namely,

$$E_c = E_r v_r + E_m v_m \tag{2}$$

where

E_c elastic modulus of composite

E_r average elastic modulus of reinforcing laminae

v_r volume fraction of reinforcing laminae

E_m elastic modulus of matrix

v_m volume fraction of matrix laminae

Deformation Behavior of Unnotched Laminar Composites

Consideration was given to the unnotched laminate failure modes and the experimentally determined stress-strain relations to obtain an indication of the deformation behavior. It was found that at least three stages of deformation observed in reference 10 for continuous fiber composites also occurred while tensile testing the laminar composites of the present investigation; they were the following:

(1) Elastic strain in the reinforcement-elastic strain in the matrix

(2) Elastic strain in the reinforcement-plastic strain in the matrix

(3) Fracturing of reinforcement and matrix

Stage 1: Elastic deformation of reinforcement, elastic deformation of matrix. - Figure 6(a) presents a load against strain curve for an unnotched low v/f reinforcement laminar composite. The stress-strain relation is linear on initial loading (i.e., the line in the region A-B is straight). This suggests that initially both constituents in the composite deformed elastically. At some elongation "B," the curve deviates from linearity and the slope becomes less. Moduli values for composites were obtained from the linear parts of the load-elongation relation. The behavior described is analogous to stage 1 deformation of fiber composites (ref. 10).

Stage 2: Elastic deformation of reinforcement, plastic deformation of matrix. - The load-strain curve given in figure 6(a) deviates from linearity at point B; that is, the slope decreased. The load-strain behavior for the low v/f composites suggested that one constituent deformed plastically. A permanent set remained in the specimen after unloading. A similar behavior was observed for all but the nominal v/f = 0.95 specimens (fig. 6(b)). Microscopic examinations of fracture of composite laminate specimens also revealed that tungsten laminae failed elastically with little or no deformation (figs. 8 to 10). The copper matrix deformed plastically. Necking of the fractured copper laminae are evident in figures 9 and 10. This behavior is analogous to stage 2 (ref. 10) found for the fiber composites.

Stage 3: Fracturing of laminar metallic composites. - Microscopic examinations of fractured specimens (figs. 8 to 10) indicated that the tungsten failed elastically in random locations in any given lamina as well as in different laminae. This behavior is indicated graphically for specimens with a v/f of 0.05 reinforcement by a serrated load-strain curve (fig. 11). Presumably, when a sufficient number of breaks in the tungsten occurred at, or close to, a given cross section, the specimen failed. Subsequent to the fracturing of the tungsten, the copper necked down in thickness and ruptured (figs. 8 to 10). This was analogous to stage 4 (ref. 10) for fiber composites. At this point it should be noted that, if the tungsten reinforcement were more ductile or if a ductile material other than tungsten were used as a reinforcement, a stage of deformation prior to fracturing, involving plastic deformation of the reinforcement and plastic deformation of the matrix, would probably have occurred that would be analogous to stage 3 (ref. 10). However, in this study, metallographic examination of the fractured composites showed no evidence of plastic deformation of the tungsten laminae within composites. Nor did measurements of tungsten laminae alone show any evidence of elongation.

In summary, the model system of unnotched laminar composites of this investigation have behaved very similarly to the model system fiber composites of reference 10. The multiple fracturing of laminae and the fact that intact copper layers were observed on either side of some cracked tungsten suggest that fracture of the weakest tungsten laminae at their weakest point did not cause catastrophic failure in the remaining laminae. After the initial cracking of the tungsten, the remaining segments appeared to perform as discontinuous reinforcing elements permitting some further strengthening of the composite.

Tensile Behavior of Notched Composites

Notched composites came close to "obeying" the ROM relation over a range of reinforcement contents extending from 0.05 to 0.60 or 0.80 volume fractions of tungsten. The actual differences between the ROM values and the LMS values decreased as the thickness of the tungsten laminae within the composites decreased. For all thicknesses of notched tungsten reinforcing laminae within the composites, linear extrapolations of the LMS curves to a v/f of 1.0 for tungsten gave tensile strength values fairly close to the measured average strength values for tungsten foil or sheet (also see table VII). The relative notched strength of the composites for the volume fractions of tungsten up to nominally 0.60 to 0.80, followed the same relative strength trends as did their included tungsten laminae. Beyond 0.60 to 0.80 v/f tungsten, the notched strengths of the composites were greatest for the composites with the thinnest laminae (0.00254 cm or 0.001 in.).

Solutions of the LMS equations to determine notched strengths of the copper laminae within the composites gave the values tabulated in table VII. The calculated values which ranged from 1.4 kN/cm^2 to 8.5 kN/cm^2 (2.0 to 12.4 ksi), were lower than the average measured strengths of the sheet (13.0 kN/cm^2 or 18.9 ksi). This is in contrast to the behavior of unnotched laminar composites where strengths of the copper laminae obtained from LMS calculations using composite data, came close to or exceeded tensile strengths of the copper sheet.

Several precautions relating to the use of ROM equations in predicting notched composite strengths from notched constituent strengths should be noted. Variations in notch sharpness and geometry as well as variations resulting from metallurgical differences can result in significant differences in the notch strength of metals. Thickness of composites could also affect notch strength. Where constituents of a composite react with each other during fabrication or during test (which can occur at high test temperatures) the phases that can form in the composite interfaces could change the notched behavior of the composite drastically relative to that predicted from tests of the constituents and the ROM equation.

Analyses of Notch Effects

The ratio of the strength of a notched specimen to the strength of an unnotched specimen is often used as a measure of a material notch sensitivity. Ratios above 1 are an indication of strengthening and below 1, weakening. For the ensuing analyses, ratios of individual strengths of notched to unnotched specimens for 0.25- and for 0.51-cm- (0.10- and 0.20-in.-) thick composite specimens were calculated and plotted in figure 12. Considerable scatter may be noted in figure 12 and horizontal bands were drawn to envelop the data points. The scatter of points precluded any observation of trends of notch strength ratios with volume fractions of reinforcements.

Figure 12 reveals that approximately two-thirds or slightly more of the notched to unnotched strength ratios calculated from the data for all types of specimens were 0.8 or better. In the case of the composites containing tungsten laminae 0.00254-cm- (0.001-in.-) thick, 20 percent of the ratios were 1 or better while for composites with tungsten laminae 0.0127-cm- (0.005-in.-) thick, 30 percent of the ratios were 1 or better. In the case of the composites with 0.0254-cm- (0.010-in.-) thick tungsten, 73 percent of the ratios were over 1, an indication of notch strengthening. Thus this method of analysis based on relative notched to unnotched strengths indicates that there is a trend toward increasing notch strengthening with increasing thickness of the tungsten laminae.

Fracture Mechanics Aspects of Notched High v/f Composites

A significant observation that may be made from the tensile strength is that two sets of high v/f tungsten-notched composites containing 0.0127- or 0.0254-cm- (0.005- or 0.010-in.-) thick reinforcing laminae had lower strengths than expected, based upon ROM curves calculated from notched tungsten sheet strengths. An explanation for this, although speculative, will be based on fracture toughness concepts. It has been observed that the tensile test data for the composites containing the highest volume fractions (>0.60) of the 0.00254-cm- (0.001-in.-) thick tungsten test specimens are uncertain because the composite test specimens failed at the pinholes. For this reason, the subsequent arguments will exclude reference to data associated with the composites containing the 0.00254-cm- (0.001-in.-) thick tungsten reinforcing laminae. The net result of the analyses, nevertheless, is believed to have practical as well as fundamental importance to the design or fabrication of composites.

Consider first a possible explanation of the fact that notch strengths of the composites with 0.0127- and 0.0254-cm- (0.005- and 0.010-in.-) thick tungsten laminae dropped off at high v/f reinforcement. One explanation might be that the copper matrix laminae are relatively thin at high v/f tungsten reinforcement. Thin layers of copper presumably would be restrained by the tungsten and cause the entire composite to behave as if it were more like bulk tungsten. It would then be logical to expect tungsten-like materials (the entire composite) to be notch weakened, which they were. Why then were the tungsten specimens (i.e., 100 percent tungsten) less notch sensitive than the high v/f composites. The reason, it is believed, is that the latter tungsten specimens were thinner (e.g., they ranged in total thickness from 0.00254- to 0.0254-cm- (0.001- to 0.010-in.-) while the tungsten-like (reinforcement-like) composites ranged in thickness from 0.254- to 0.508-cm- (0.10- to 0.20-in.-). It is well known that thicker materials (even ductile materials) can be made to fracture in a more brittle manner when notched because plane-strain fracture (ref. 14) is involved.

SUMMARY OF RESULTS AND CONCLUSIONS

This investigation, a study of laminar composites composed of mutually insoluble laminae of tungsten and copper (a "model system"), yielded the following major results and conclusions:

1. The ultimate tensile strength and moduli of elasticity of unnotched composites could be related to the strength and moduli of the constituents comprising the composites by rule-of-mixtures (ROM) equations. The fact that the composites "obeyed" the ROM relations indicates that each constituent of the composite contributed its full ultimate tensile strength, in one case, or stiffness, in the other case, to the composite in direct relation to the quantity of the constituent.

2. In general, the unnotched laminar composites of tungsten reinforced copper of this investigation behaved very similarly to unnotched tungsten fiber reinforced copper composites investigated previously by others. Both types of composites obeyed a ROM relation between composite strengths and strengths of constituents. Minimal additions of reinforcing laminae to the copper should cause strengthening of a laminar composite, whereas for fiber composites a critical volume fraction would be required to exceed the ultimate tensile strength of the matrix.

3. The fracture behavior of the unnotched laminar composites studied was similar to that of fiber composites in that failure of individual reinforcements did not cause catastrophic failures of the composite. Multiple fracturing of laminae was observed and intact copper layers were found on either side of some cracked tungsten reinforcements in failed specimens.

4. Strength of unnotched composites increased with decreasing thickness of the tungsten laminae reinforcements. This effect was believed to be related solely to the strength of the laminae which also increased with decreasing thickness.

5. No pronounced effects of reinforcing laminae thickness on moduli of unnotched composites was evident from the data. However, composites with the thinnest reinforcing laminae (0.00254-cm- or 0.001-in.- thick tungsten) had, for the most part, somewhat greater moduli than did the other composites.

6. Three stages of deformation were observed for unnotched composites, namely, elastic deformation of the reinforcement and matrix; elastic deformation of the reinforcement, plastic deformation of the matrix; and fracture. It was suggested that a stage prior to fracture would occur if the reinforcement were ductile, namely, plastic deformation of the reinforcement and matrix.

7. For the notched composites containing 0.00254-cm- (0.001-in.-) thick tungsten laminae, the relation between tensile strength and volume fraction reinforcement was linear up to at least 0.60. Tensile strength curves for notched composites with 0.0127- and 0.0254-cm- (0.005- and 0.010-in.-) thick tungsten laminae were linear with volume fraction of reinforcement to nominal values of 0.6 and 0.8, respectively.

8. The ultimate tensile strengths of notched laminar composites with a range of tungsten reinforcement content extending from a volume fraction of 0.05 to 0.60 or 0.80 could be related to the ultimate tensile strengths of the notched constituents comprising the composites. Generally, the aforementioned notched composites came close to obeying the ROM relations.

9. A comparison of the ratios of strength of individual notched to unnotched composites of like volume fraction reinforcement and thickness revealed no constant relation between notch strength ratios and volume fraction reinforcement. However, notch to unnotched ratios (over 0.8) were observed for wide ranges of volume fractions of reinforcement for composites with each thickness of tungsten laminae. In fact, approximately two-thirds of the notched to unnotched strength ratios calculated for all composites studied were above 0.8.

10. There appeared to be a trend toward increasing notch strengthening with increasing thickness of the tungsten laminae. In the case of composites containing tungsten laminae 0.00254 cm (0.001 in.) thick, 20 percent of the ratios were 1.0 or better while for composites with tungsten laminae 0.0127 cm (0.005 in.) thick, 30 percent of the ratios were 1.0 or better. In the case of the composites with 0.0254-cm- (0.010-in.-) thick tungsten, 73 percent of the ratios were over 1.0, an indication of notch strengthening.

CONCLUDING REMARKS

The evidence obtained in this investigation has shown that laminar composites of the mutually nonreactive materials, tungsten and copper, behaved similarly in tensile tests to fiber composites of the same materials studied by earlier investigators. Specifically, the laminar composites of this study and the fiber composites studied earlier had strengths which may be represented by the rule-of-mixtures (ROM) relation for a wide range of reinforcement sizes and volume fractions.

Since strengths of composites obeying the ROM relation depend on the strengths of the constituents comprising the composite, it would be desirable to have ultra high strength reinforcing sheet or foil materials. At the present time, the available sheet does not have strengths equal to those of the strongest fibers. Thin films which have been made by vapor deposition methods sometimes have very high strength, but in general, are not as strong as fibers. Furthermore, very few materials have been made with the intention of using them as reinforcements in laminated composites. Even so, some rolled plate and sheet metals and alloys which have been made for other uses and some thin films have strengths great enough to warrant their consideration for use as reinforcements in multilayered, laminar composites.

Structures subjected to a biaxial stress state may preferably be made from laminar rather than fiber composites. A rotor disk, made from sheets for example, may not only be made to have nearly isotropic properties in the plane of the rotor, but should have lower microstress concentrations than a cross plied, multilayered fiber reinforced rotor. Laminar composites with a weaker reinforcing phase than that of a fiber composite, could have a greater planar "isotropic" strength than would the fiber composite, particularly if, in both cases the matrix phase were weak.

Some examples of applications (room or low temperature) of laminar composites that might be considered are: hollow tubular structures, high pressure tanks, structural stiffeners, gusset plates, channels, cryogenic tanks, pipes, and bulkheads. High temperature uses may also be anticipated; for example, turbine blades, vanes, combustion chambers, high temperature pressure preburner chambers, chambers for advanced rocket engines, thrust reversers, reentry vehicle edges, and nuclear or other furnace components. Very large diameter turbine rotor disks of almost any size for electric power generation turbines may conceivably be made by interlayering and bonding or brazing materials, whereas the sizes of conventional disks are usually limited by the size of the forging press.

Various combinations of metal/metal laminar composites should not only be usable in the "as-consolidated" condition; but subsequent to consolidation, some combinations of materials should be rollable, forgeable, bendable, deep drawn, and otherwise shaped by numerous metal-working practices.

In general, the results of this study indicated that not only were many laminar composites notch insensitive, but some were notch strengthened. The notch study portions of this investigation must be considered preliminary in nature. Although the data obtained and the variables investigated were limited, particularly when one considers the many variables that may affect notch strength of materials, the results suggest that, in the future, laminar composites not only may be made to have high strength but in some cases may be made notch insensitive. High strength monolithic materials that are subject to catastrophic brittle fracture may conceivably be replaced with laminar composites. Future studies to investigate the large numbers of variables affecting notch strength and fracture toughness of laminar composites appear to be warranted.

Considering the possibilities for applications of laminar composites noted previously and the potential for increasing the strength of laminar composites by increasing strength of reinforcing laminae, effort should be expended to develop high strength sheet and foil specifically intended for use in laminar composites. Furthermore, novel ways of producing laminar composites, such as by vapor deposition of metals and ceramics, should also be considered in the future.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 24, 1976,
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TABLE I. - THICKNESS AND COMPOSITION OF MATERIALS USED FOR SPECIMENS

Material	Thickness		Composition[a, b]																	
	cm	in.	Al	Cd	Si	Cr	Fe	Ni	Mn	Mg	Sn	Mo	Co	Zr	O_2	C	N_2	H_2	Cu	W
Copper	0.00381	0.0015																	[c]99.92 wt. %	
	.01651	.0065																		
	.03302	.013																		
	.2413	.095																		
Tungsten	0.00254	0.001	--	--	--	--	20	--	--	--	--	200	--	--	30	30	10	6	--	Balance
	.0127	.005	<6	3	<7	3	13	12	<6	4	<6	45	<3	<3	--	--	--	--	<3	Balance
	.0254	.010	<6	3	<7	3	13	12	<6	4	<6	45	<3	<3	--	--	--	--	<3	Balance

[a]Compositions furnished by vendor.

[b]Values given in ppm unless otherwise indicated.

[c]OFHC copper (nominal composition), trace elements not reported.

TABLE II. - CONSTITUTION OF UNNOTCHED AND NOTCHED LAMINAR COMPOSITE TEST SPECIMENS

Specimen type[a]	Tungsten laminae thickness			Copper laminae thickness			Volume fraction of tungsten
	cm	in.	Number	cm	in.	Number	
1A	0.00254	0.001	10	0.04445	0.0175	11	0.05
1B			5	.04445	.0175	6	.05
2A			40	.00965	.0038	41	.20
2B			20	.00965	.0038	21	.20
3A			80	.00381	.0015	81	.39
3B			40	.00381	.0015	41	.39
4A			120	.00127	.0005	121	.58
4B			60	.00127	.0005	61	.58
5B			80	.00635	.00025	81	.78
6A			190	.000254	.0001	191	.95
6B			95	.000254	.0001	96	.91
7A	0.0127	0.005	2	0.16256	0.064	3	0.05
8A			8	.04375	.0175	9	.20
8B			4	.04375	.0175	5	.19
9A			16	.01651	.0065	17	.42
9B			8	.01651	.0065	9	.42
10A			24	.007112	.0028	25	.63
10B			12	.007112	.0028	13	.62
11B			16	.00381	.0015	17	.76
12A			48	.000635	.00025	49	.95
12B			24	.000635	.00025	25	.95
13A	0.0254	0.010	1	0.2413	0.095	2	0.05
14A			4	.08128	.032	5	.20
14B			2	.08128	.032	3	.17
15A			8	.03302	.013	9	.41
15B			4	.03302	.013	5	.38
16A			12	.01651	.0065	13	.59
16B			6	.01651	.0065	7	.57
17A			16	.007112	.0028	17	.79
17B			8	.007112	.0028	9	.80
18A			19	.00127	.0005	20	.95
18B			10	.00127	.0005	11	.94

[a]Type A specimens were nominally 0.508 cm (0.20 in.) thick; type B specimens were 0.254 cm (0.10 in.) thick.

TABLE III. - TENSILE RESULTS OBTAINED FOR TUNGSTEN SHEET SPECIMENS AT ROOM TEMPERATURE

Thickness		Ultimate tensile strength (unnotched)		Ultimate tensile strength (notched)	
cm	in.	kN/cm²	ksi	kN/cm²	ksi
0.00254	0.001	190.0	276.0	80.5	116.8
		146.1	212.0	122.1	[a]176.9
		201.0	292.0	165.6	[a]240.0
		-----	-----	159.0	[a]230.0
		-----	-----	131.4	190.9
Average		179.0	260.0	131.4	190.7
Standard deviation		29.1	42.3	33.8	49.1
0.0127	0.005	128.6	186.4	176.0	255.0
		133.9	[a]194.1	153.2	[a]222.0
		130.4	189.0	131.8	191.0
		131.8	191.0	161.0	232.0
		165.0	239.2	168.4	[a]244.0
		157.3	[a]228.0	200.1	290.0
		190.4	[a]276.0	-----	-----
Average		148.2	214.8	164.7	239.0
Standard deviation		23.5	34.1	22.9	33.2
0.0254	0.010	131.2	190.2	109.3	158.6
		122.1	177.0	192.0	278.2
		122.1	177.0	167.5	242.7
Average		125.1	181.4	156.1	226.5
Standard deviation		5.2	7.5	42.3	61.4

[a]Specimen tested with fixture illustrated in fig. 3.

TABLE IV. - TENSILE RESULTS OBTAINED FOR COPPER SHEET AT ROOM TEMPERATURE

Thickness		Ultimate tensile strength (unnotched)		Percent elonga-tion	Ultimate tensile strength (notched)		Percent elonga-tion
cm	in.	kN/cm²	ksi		kN/cm²	ksi	
0.00381	0.0015	15.5	22.4	8	9.6	13.9	10
		10.4	15.1	11	12.1	17.6	8
Average		13.0	18.8	10	10.8	15.7	9
0.01651	0.0065	17.0	24.6	30	12.8	18.6	15
		17.7	25.6	27	12.8	18.6	11
Average		17.3	25.1	28	12.8	18.6	13
0.03312	0.013	12.6	18.3	43	8.7	12.7	20
		13.5	19.5	48	9.1	13.2	36
Average		13.0	18.9	46	8.9	13.0	28
0.2413	0.095	17.4	25.2	53	18.7	27.1	38
		17.1	24.8	56	20.7	30.0	38
Average		17.2	25.0	55	19.7	28.6	38
Overall average		15.1	21.9	--	13.0	18.9	--

TABLE V. - TENSILE RESULTS OBTAINED FOR TUNGSTEN/COPPER LAMINAR COMPOSITES AT ROOM TEMPERATURE

Specimen[a]	Thickness of tungsten		Volume fraction of tungsten reinforcement	Ultimate tensile strength (unnotched)		Percent elongation	Ultimate tensile strength (notched)		Percent elongation
	cm	in.		kN/cm^2	ksi		kN/cm^2	ksi	
1A	0.00254	0.001	0.05	17.8	25.8	13	17.3	25.1	5
1B			.05	23.6	34.2	12	16.2	23.5	0
2A			.20	35.8	52.0	0	32.3	46.8	0
2B			.20	38.7	56.2	0	26.0	37.7	0
3A			.39	61.5	89.3	0	61.5	89.3	0
3B			.39	66.6	96.7	0	35.6	51.7	0
4A			.58	90.2	130.9	0	81.2	117.8	0
4B			.58	103.7	150.5	0	35.7	141.7	0
5B			.78	120.6	175.0	0	119.4	[b]173.0	0
6A			.95	138.9	[c]200.0	--	-----	-----	-
6B			.91	137.5	199.5	0	113.6	[b]164.8	0
7A	0.0127	0.005	0.05	19.2	27.8	16	18.8	27.2	9
8A			.20	36.9	53.5	1	26.8	38.9	0
8B			.19	33.3	48.3	2	25.1	36.4	0
9A			.42	75.5	109.5	0	66.4	96.3	0
9B			.42	73.5	106.7	0	61.7	89.4	0
10A			.63	81.9	118.9	0	90.7	131.4	0
10B			.62	96.5	140.0	0	111.0	160.8	0
11B			.76	122.5	177.8	0	89.2	129.3	0
12A			.95	138.9	[c]200.0	--.	103.3	150.0	0
12B			.95	114.2	165.7	0	82.5	119.8	0
13A	0.0254	0.010	0.05	16.7	24.3	28	20.5	29.7	7
14A			.20	37.9	55.0	9	26.2	38.0	0
14B			.17	34.3	49.8	8	38.9	56.4	0
15A			.41	46.5	67.5	0	48.1	69.7	0
15B			.38	64.9	94.2	0	70.0	101.5	0
16A			.59	92.7	134.6	0	95.6	138.7	0
16B			.57	89.4	129.7	0	49.8	72.2	0
17A			.79	101.4	147.2	0	111.4	161.7	0
17B			.80	107.4	155.8	0	124.5	180.4	0
18A			.95	76.7	111.3	0	99.2	144.0	0
18B			.94	139.5	202.5	0	109.3	158.6	0

[a]Type A specimens were nominally 0.508 cm (0.2 in.) thick; type B specimens were nominally 0.254 cm (0.1 in.) thick.

[b]Specimen failure outside of test zone.

[c]Specimen initially failed in tension at pin hole. It was then retested using jaw clamps. Specimens withstood maximum stress applied, that is, 138.9 kN/cm^2 (200 ksi).

TABLE VI. - ELASTIC MODULI FOR TUNGSTEN/

COPPER LAMINAR COMPOSITES[a]

Tungsten laminae thickness		Volume fraction of tungsten	Elastic modulus	
cm	in.		MN/cm^2	Mpsi
0.00254	0.001	0.05	10.5	15.2
		.20	17.9	26.0
		.39	24.7	35.8
		.58	29.4	42.7
		.78	35.9	52.1
		.91	38.5	55.9
0.0127	0.005	0.19	15.4	22.3
		.42	24.0	34.8
		.62	30.0	43.5
		.76	33.0	47.8
		.95	39.0	56.5
0.0254	0.010	0.17	18.1	26.2
		.38	20.4	29.6
		.57	29.1	42.2
		.80	33.9	49.1
		.94	37.0	53.8

[a]Specimens were 0.254 cm (0.10 in.) thick.

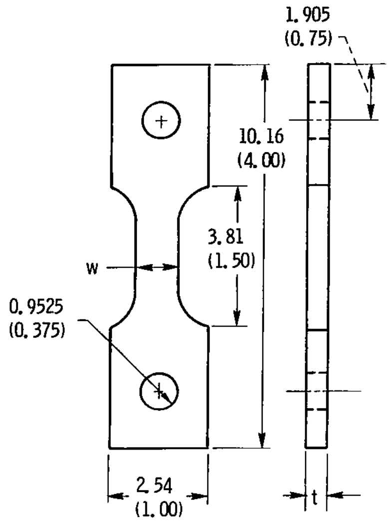
TABLE VII. - AVERAGE EXPERIMENTAL AND CALCULATED ULTIMATE

TENSILE STRENGTHS OF TUNGSTEN LAMINAE

Composite specimen	Tungsten thickness		Average strength of copper sheet (measured)		Average strength of copper laminae obtained from least-mean-square equation for composite specimens		Average strengths of tungsten sheet (measured)		Average strength of tungsten laminae obtained from least-mean-square equation for composite specimens	
	cm	in.	kN/cm^2	ksi	kN/cm^2	ksi	kN/cm^2	ksi	kN/cm^2	ksi
Unnotched	0.00254	0.001	----	-----	11.7	17.0	179.0	260.0	151.9	220.4
	.0127	.005	----	-----	16.7	24.2	148.2	214.8	135.7	196.8
	.0254	.010	----	-----	17.8	25.8	125.0	181.3	122.4	177.6
	Average		15.1	[b]21.9	15.4	22.3	-----	-----	-----	-----
Notched	0.00254	0.001	----	-----	4.9	7.1	131.4	191.7	139.5	202.5
	.0127	.005	----	-----	1.4	2.0	164.7	239.8	155.7	225.8
	.0254	.010	----	-----	8.5	12.4	156.1	226.5	136.8	198.4
	Average		13.0	[b]18.9	4.9	7.2	-----	-----	-----	-----

[a]Results of tensile tests made of tungsten specimens tested separately.

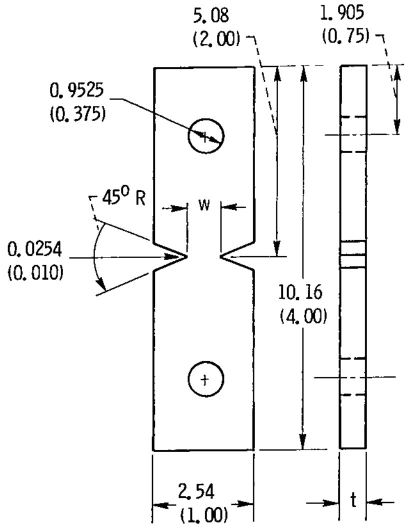
[b]Average experimental values for all copper sheet and foil taken from table IV.



Type of specimen	Width		Thickness	
	cm	(in.)	cm	(in.)
A composite (see table II)	0.9525	(0.375)	0.508	(0.20)
B composite (see table II)	.535	(.25)	.254	(.10)
Sheet or foil	.9525	(.375)	(*)	(*)

*See tables III and IV.

Figure 1. - Unnotched tensile specimen. (All dimensions given in cm (in.).)



Type of specimen	Width		Thickness	
	cm	(in.)	cm	(in.)
A composite (see table II)	0.9525	(0.375)	0.508	(0.20)
B composite (see table II)	.535	(.25)	.254	(.10)
Sheet or foil	.9525	(.375)	(*)	(*)

*See tables III and IV.

Relative orientation of notch and laminae

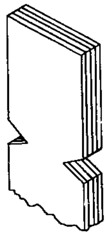


Figure 2. - Notched tensile specimen. (All dimensions given in cm (in.).)

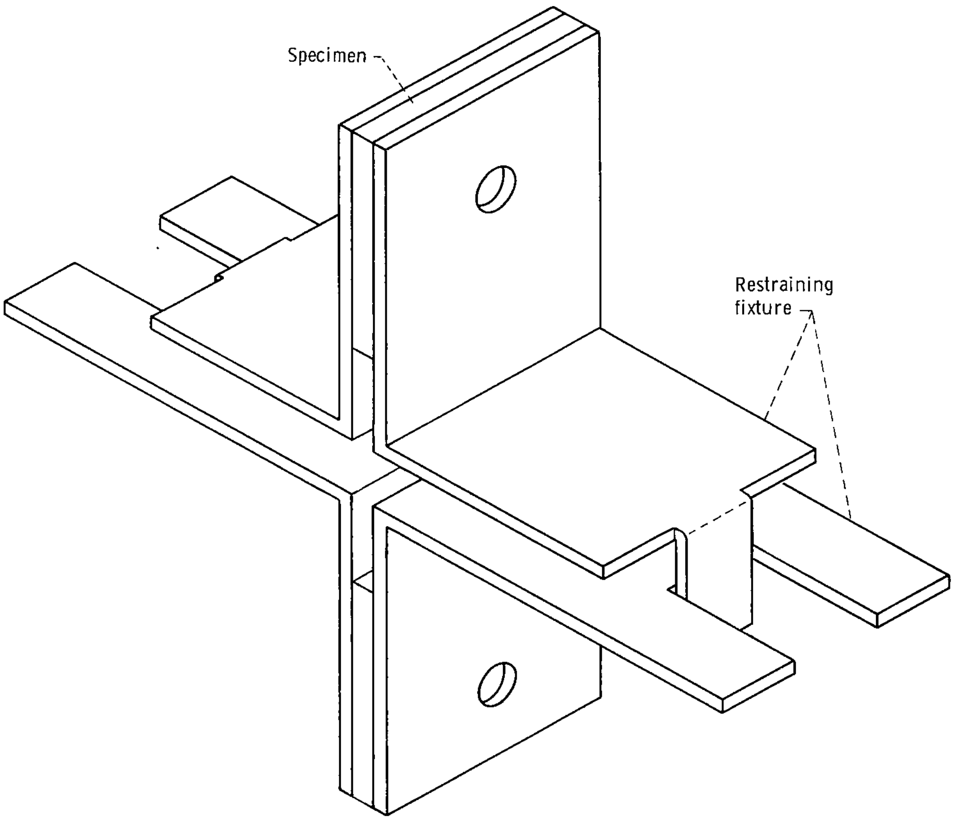
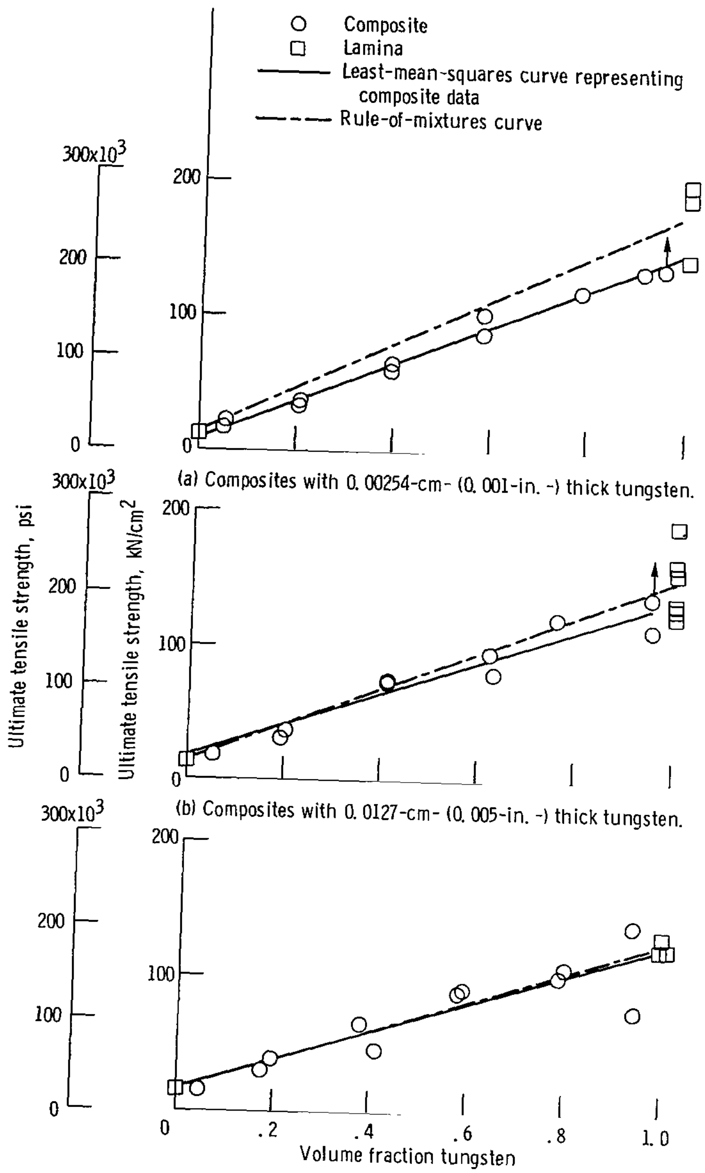


Figure 3. - Schematic illustration of restraining fixture attached to thin sheet specimens.



(c) Composites with 0.0254-cm- (0.010-in.-) thick tungsten.

Figure 4. - Room temperature tensile strength plotted against volume fraction reinforcement for unnotched tungsten/copper laminar composites.

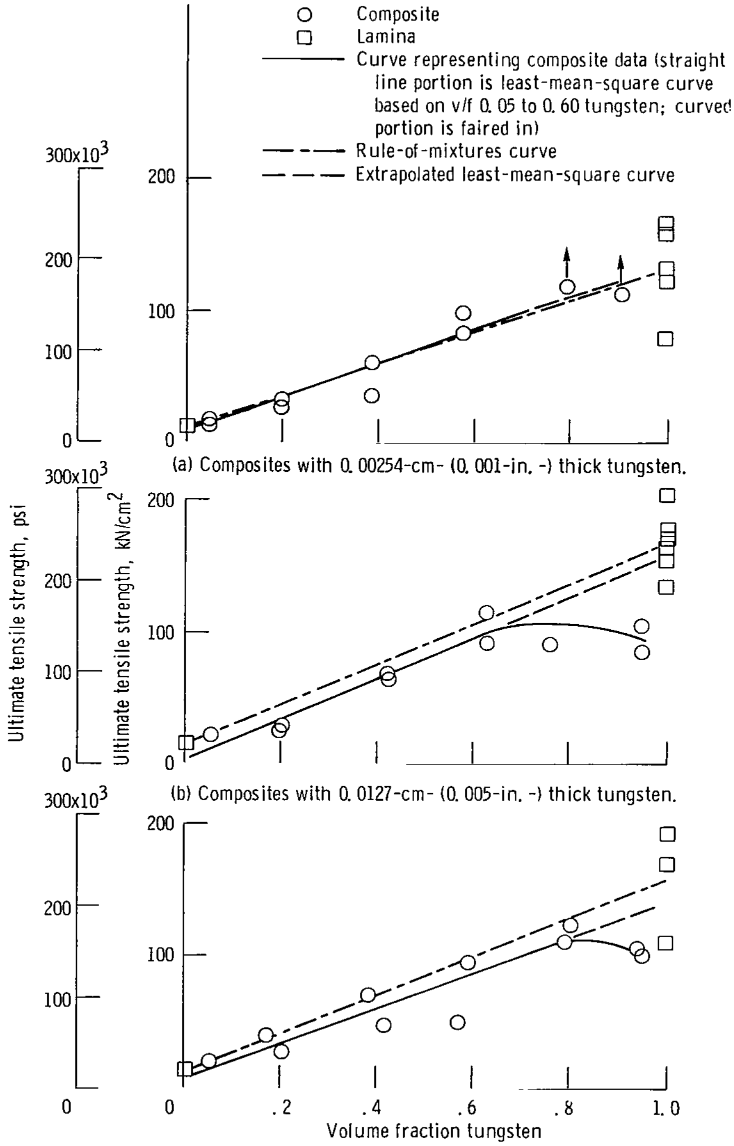


Figure 5. - Room temperature tensile strength plotted against volume fraction of reinforcement for notched tungsten/copper laminar composites (K_t = 5.8).

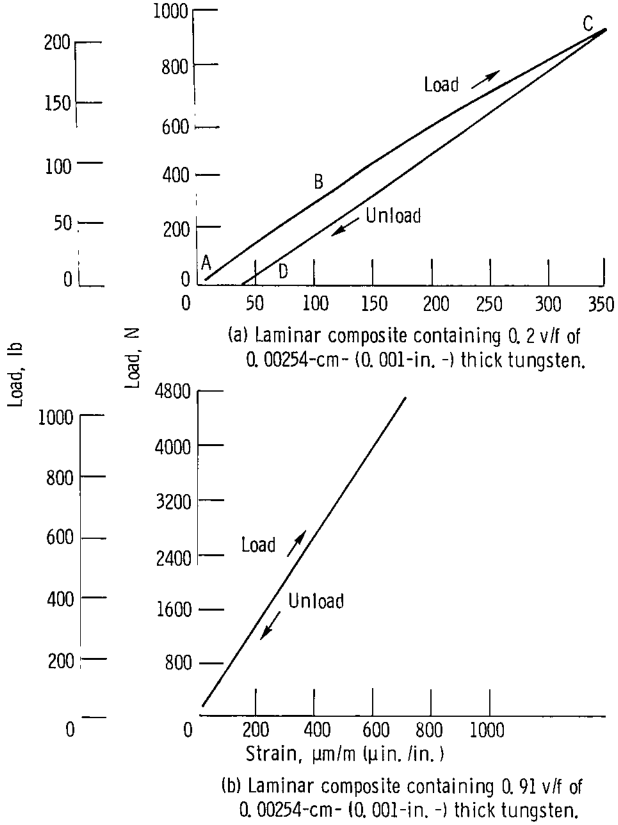


Figure 6. - Examples of load-strain curves for unnotched laminar composites.

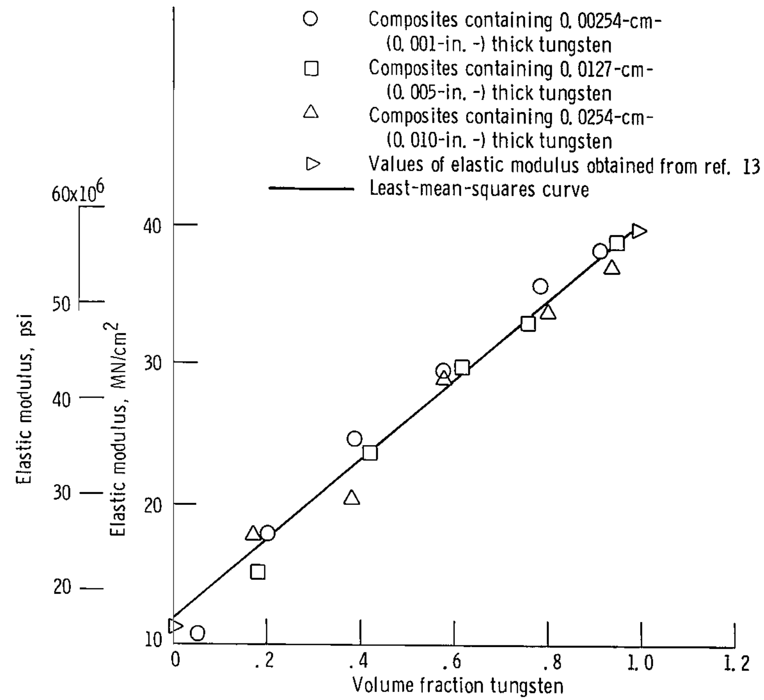
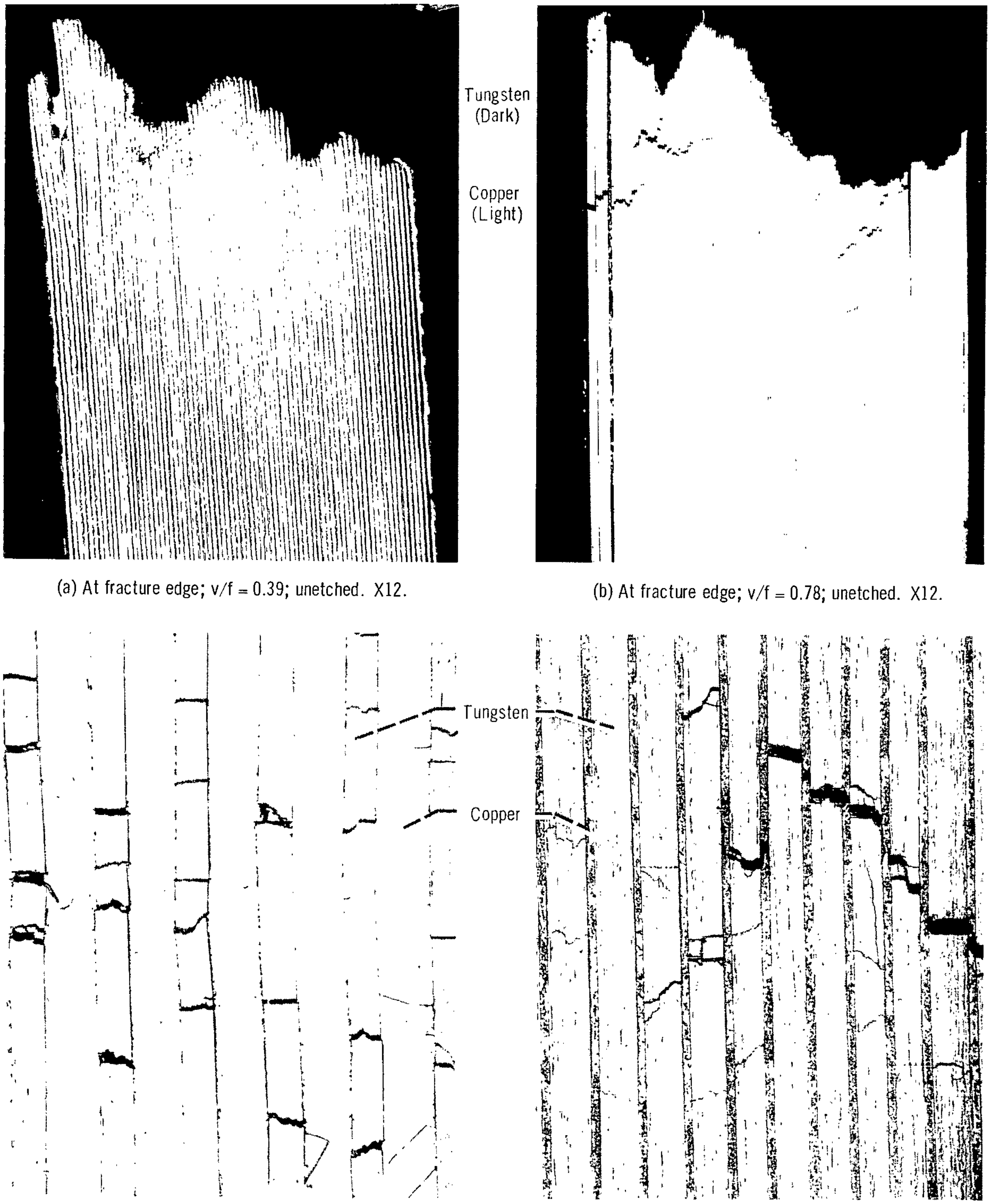


Figure 7. - Elastic modulus plotted against volume fraction of tungsten reinforcement for unnotched tungsten/copper laminar composites at room temperature.



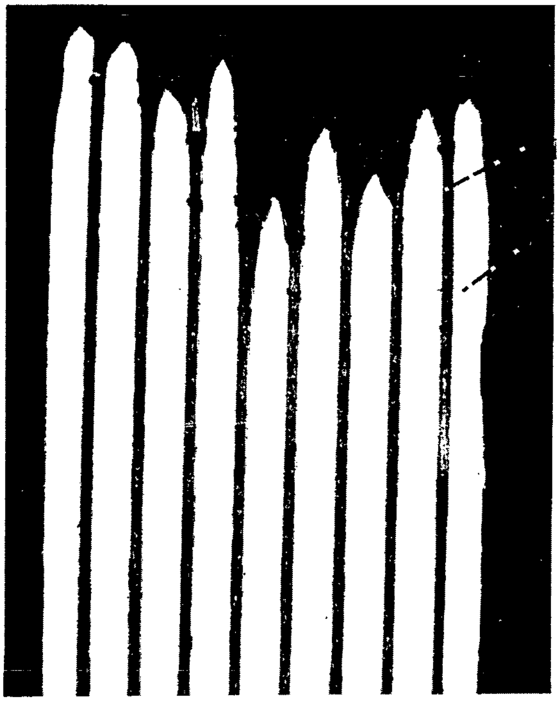
(a) At fracture edge; v/f = 0.39; unetched. X12.

(b) At fracture edge; v/f = 0.78; unetched. X12.

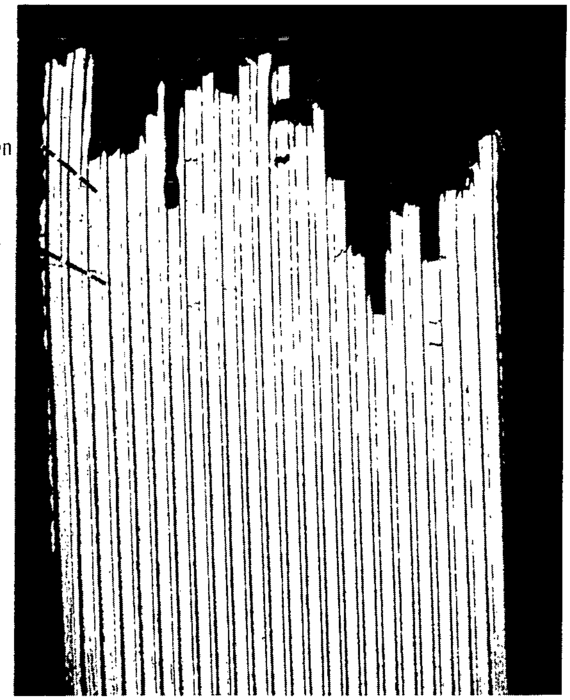
(c) Area adjacent to fracture edge; v/f = 0.39; unetched. X250.

(d) Area adjacent to fracture edge; v/f = 0.78; etched (3 pts NH_4 + 1 pt H_2O_2). X250.

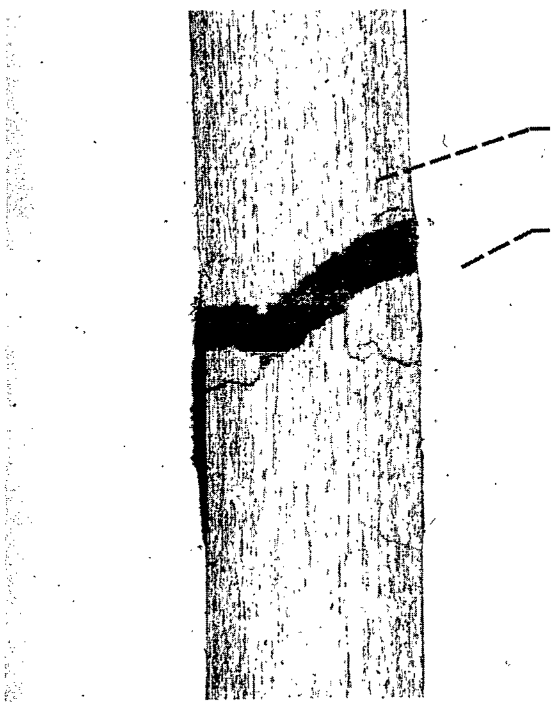
Figure 8. - Fractured specimens with 0.00254-cm - (0.001-in.-) thick tungsten laminae. (Reduced 17 percent in printing.)



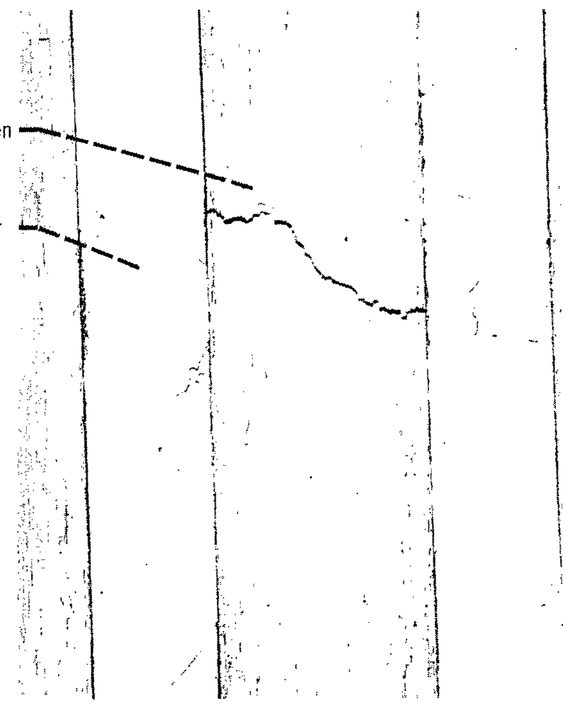
(a) At fracture edge; v/f = 0.20; unetched. X12.



(b) At fracture edge; v/f = 0.62; unetched. X12.

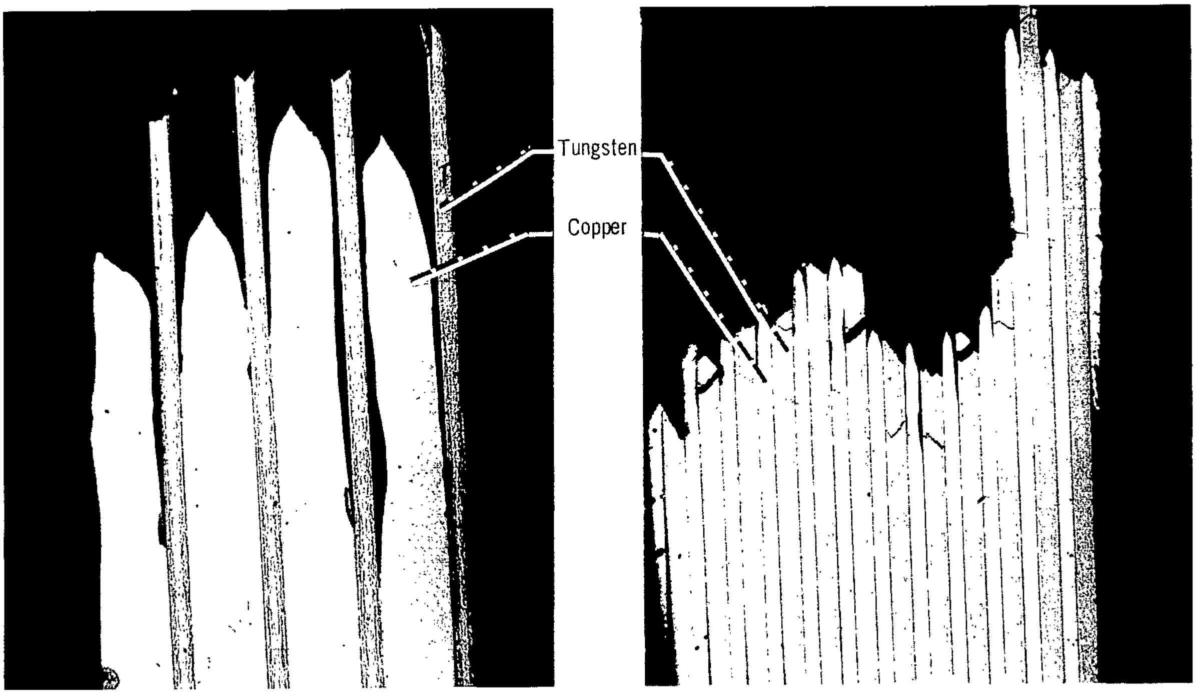


(c) Area adjacent to fracture edge; v/f = 0.20; unetched. X250.



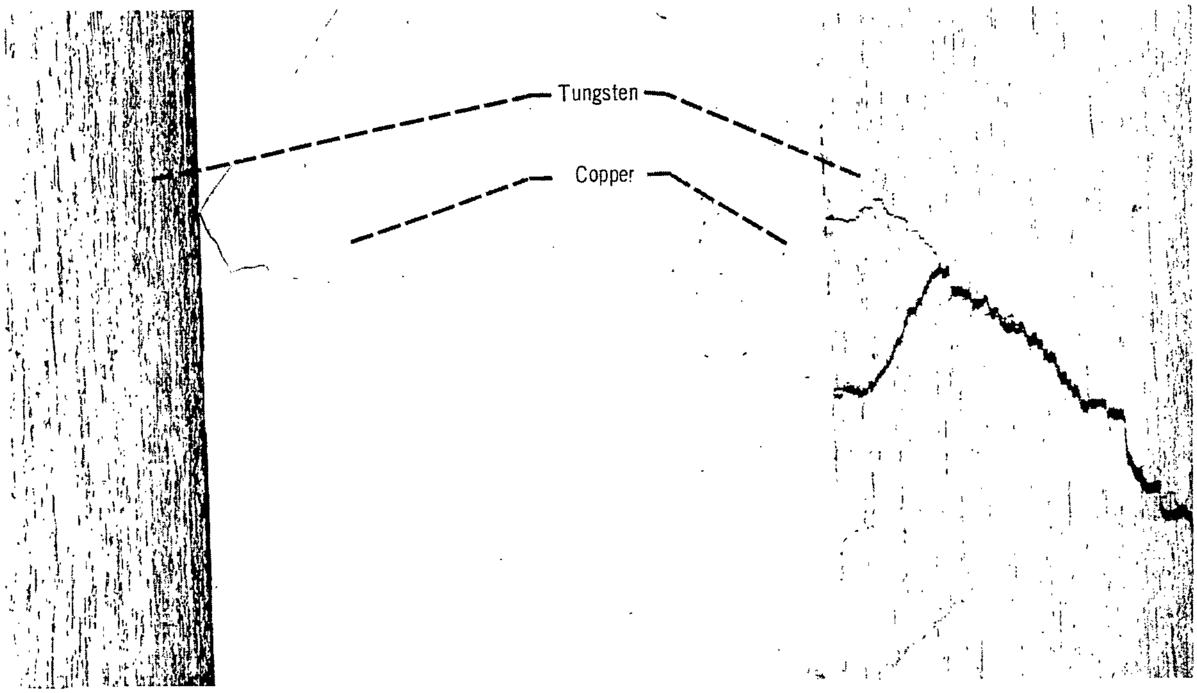
(d) Area adjacent to fracture edge; v/f = 0.62; unetched. X250.

Figure 9. - Fractured specimens with 0.0127-cm - (0.005-in.-) thick tungsten laminae. (Reduced 17 percent in printing.)



(a) At fracture edge; v/f = 0.17; unetched. X12.

(b) At fracture edge; v/f = 0.57; unetched. X12.



(c) Area adjacent to fracture edge; v/f = 0.17; unetched. X250.

(d) Area adjacent to fracture edge; v/f = 0.57; unetched. X250.

Figure 10. - Fractured specimens with 0.0254-cm - (0.010-in.-) thick tungsten laminae. (Reduced 17 percent in printing.)

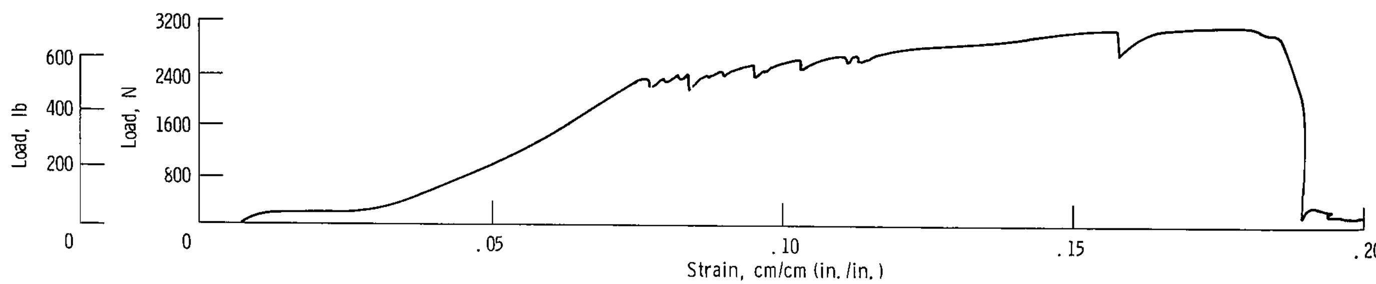


Figure 11. - Load-strain curve for laminar composite containing 0.05 v/f of 0.00254-cm- (0.0001-in.-) thick tungsten. Tested at room temperature; crosshead speed, 0.127 cm/min (0.05 in./min); chart speed, 12.7 cm/min (5 in./min).

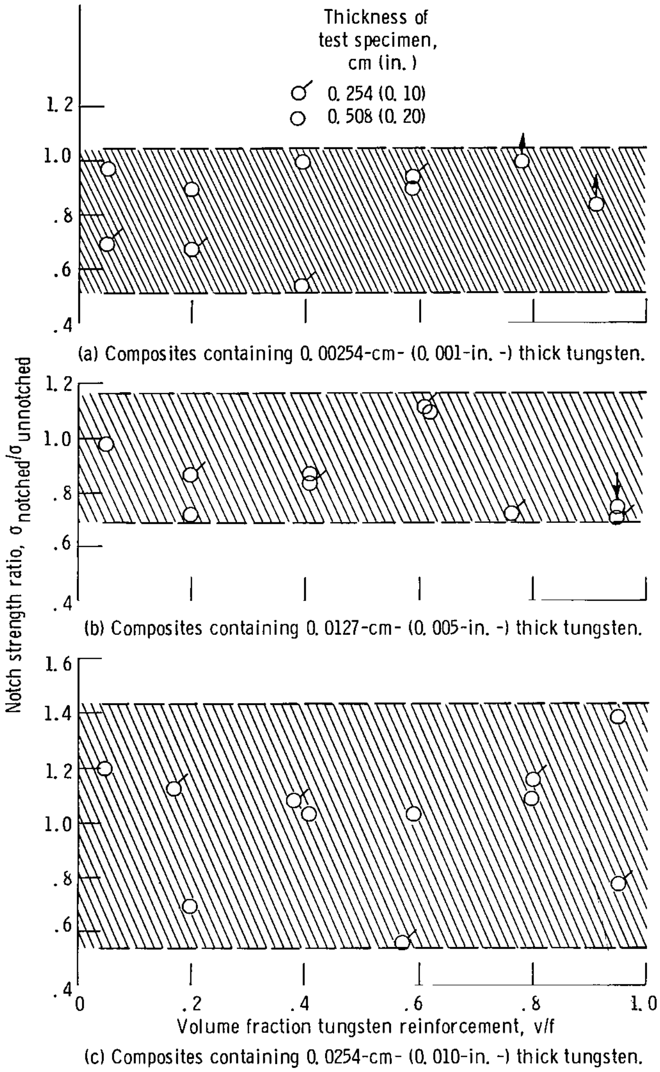


Figure 12. - Ratios of notched to unnotched ultimate tensile strengths of tungsten/copper laminar composites tested at room temperature.

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