Metal matrix composite materials

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COMPOSITE materials, especially metal matrix composite materials are possible substitutes for metals in use today. However, because they can possess extremely high strengths, moduli and excellent high temperature properties they may be employed most profitably in applications which do not presently exist, since no present material has the required capabilities. In addition, their present high cost and very early stage of development make them unlikely candidates for materials substitution in the context of this meeting. This paper is oriented more towards the development of composite materials for aerospace structures.

Ultimately composite materials, especially metal matrix composites may become vital materials in the industrial growth of a nation. The employment of composite technology may permit the large scale substitution of aluminium for the more scarce metal copper in high voltage electrical transmission. The improved strength and strength retention at temperature of axially reinforced aluminium composites would permit significant increases in the power carrying capability of the aluminum due to the high permissible operating temperatures. In addition, other significant savings would be found in the ability of the composite to support its weight over longer distances due to higher tensile strength and improved creep resistance. This could reduce the number of support structures by more than a factor of two. This brief example is only one of the potential ways in which these new metal matrix composite materials can ultimately provide a better life for us all.

Glass filament-polymeric matrix composites already have become familiar materials in uses ranging from light-weight luggage to high performance solid propellant rocket motor cases. During the last decade there have been a few developments—oriented attempts to incorporate glass or metal wire filaments in metal matrices, but these did not generate any significant practical enthusiasm. Some work with such filament-matrix combinations, particularly during the last few years, has been very valuable from the viewpoint of model system information to stimulate and verify theoretical micromechanics. The latter involves analysis of stress and strain distribution between components of the composite, and prediction of composite properties from the properties of the components and the geometry of the microstructure. Comprehensive reviews of the literature on filament-metal matrix composites have recently appeared.[1,2]

The simple concepts of reinforcement in unidirectional composites have been fairly well established. Thus, the work of McDanels, Jech, and Weeton[3] in Fig. 1 shows that the modulus of a copper matrix-continuous tungsten wire composite can be predicted by a linear rule of mixtures.

$$E_c = E_f V_f + E_m (1 - V_f)$$

Where E is modulus, V is volume fraction of a component, and the subscripts c, f, and m refer to composite, filament and matrix, respectively. In a composite containing discontinuous filaments, shear within the matrix is necessary to transfer the load to and between the filaments. The work of Sutton and Chorne,[4] for example, shown in Fig. 2 for the model system of Al_2O_3 whiskers in silver demonstrates that reinforcement can occur. The shear strength of the matrix and of the bond developed between the filament and the matrix in these specimens is sufficient to permit most of the strength of the filaments to be developed in the composite. Again, a simple linear rule of mixtures provides a relatively good fit of these data. Some preliminary work from our own laboratory, such as on the boron filament-metal matrix composites shown in Fig. 3 also demonstrates that significant reinforcement can occur. For 7·5 volume per cent filament the strength and modulus of this specimen were increased by 17 per cent and 27 per cent respectively over that of the unreinforced matrix.

Interest in metal matrix composites received its most significant stimulus from the emergence of a variety of new, high modulus, high strength, low density and often refractory filamentary materials. Table I shows the properties of a few of these and of some typical glass and metal filaments. To a first approximation, the distribution of stress between the components of a composite will be in proportion to their moduli of elasticity. Thus, since the moduli of some of these filaments are significantly greater than those of potential metal matrices such as aluminum, titanium, or even steel and nickel, they can act as efficient reinforcements. Since, in addition, their

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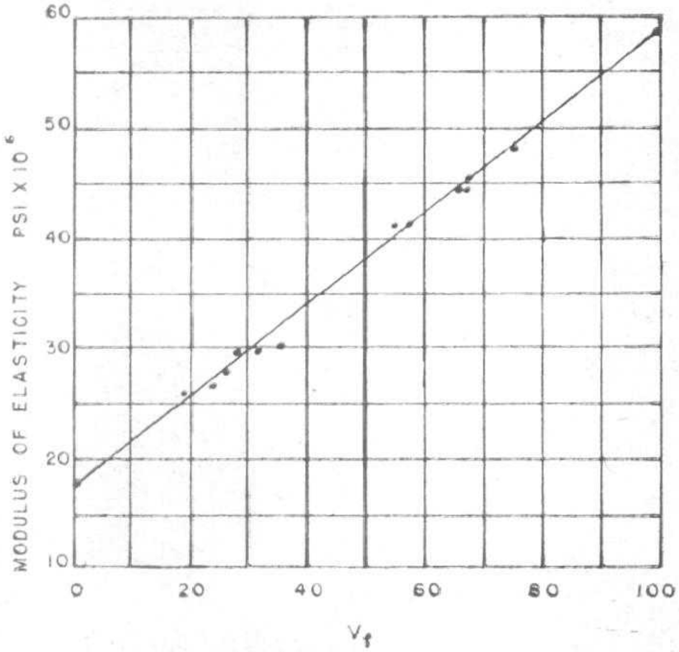
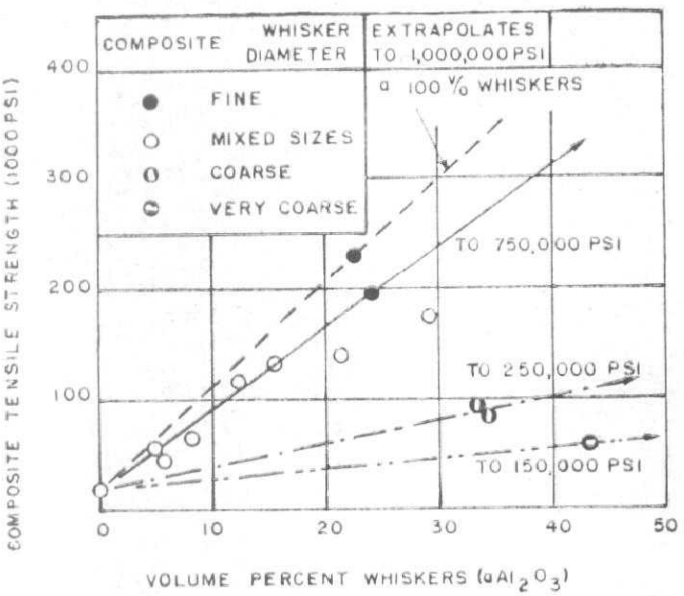
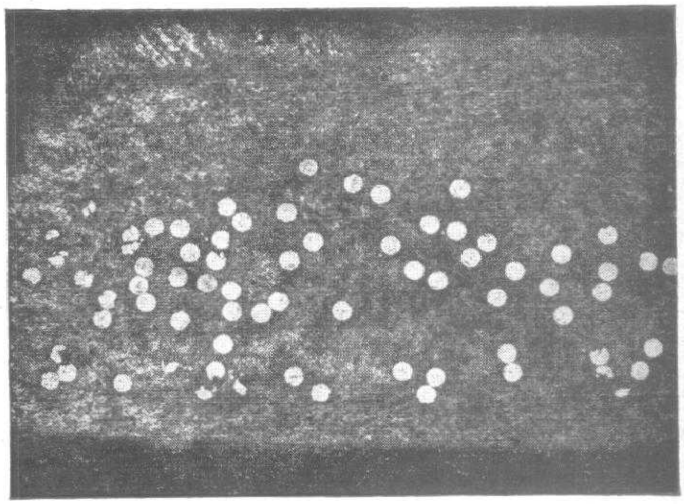


1 *Dynamic modulus of elasticity of tungsten, copper, and copper reinforced with tungsten wires (McDANELS ET AL (4))*



2 *Tensile strength of silver-alumina whisker composites (Sutton and Chorne (7))*



3 *Macrostructure of aluminium-boron composite which exhibits fiber reinforcement* ×25

densities are low, improved strength to weight ratios are potentially attainable in metal matrix composites with these filaments. The availability of a variety of these as continuous filaments, and the promise of more such as high modulus, high strength carbon filaments, has led to a major acceleration of activity and interest in metal matrix composites.

TABLE I Filament properties

Material	Tensile strength, psi	Elastic modulus, psi	Density, lbs./in.^{3}	Strength/Density, in.
Beryllium	180	45×10^6	0·066	$2·73\times10^6$
Molybdenum	320	48 ,,	0·369	0·88 ,,
Steel	600	29 ,,	0·283	2·12 ,,
Tungsten	580	59 ,,	0·697	0·83 ,,
E-Glass	350	10 ,,	0·092	3·81 ,,
Silica	500	10 ,,	0·079	6·35 ,,
Boron	400	55 ,,	0·083	4·82 ,,
Carbon	200	25 ,,	0·060	2·17 ,,
Silicon carbide	400	70 ,,	0·142	2·79 ,,
Alumina whiskers	2000	75 ,,	0·143	24·50 ,,
Graphite whiskers	350	45 ,,	0·060	5·84 ,,
Silicon carbide whiskers	1500	123 ,,	0·115	13·00 ,,
Zirconia whiskers	126	26 ,,	0·200	0·63 ,,

The current activity in this field in our own laboratory and in the United States in general can be divided into the following major categories :

(a) Development and characterization of filaments.

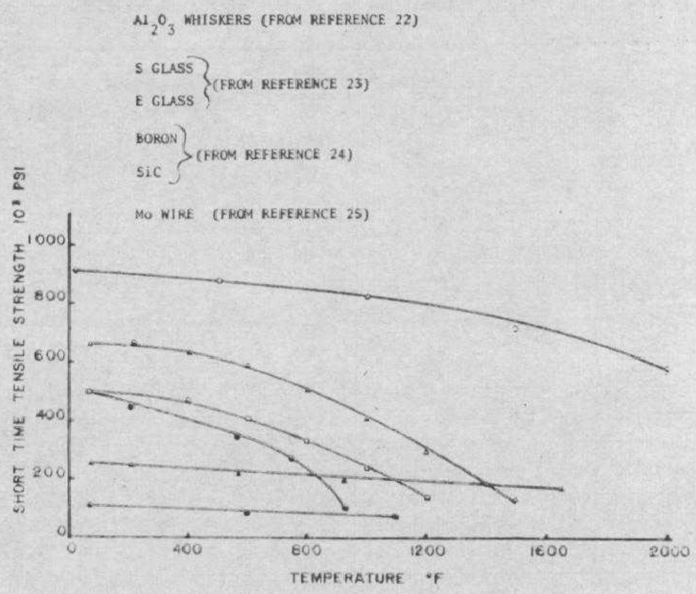
(b) Analysis of the micromechanics of composites; i.e., of the detailed nature of the stress and strain distribution among the components of a composite as a function of external loading.

(c) Study of filament-matrix interactions, including the nature of the interfaces and the reactivity or stability of the components (chemical reaction, dissolution, etc.) towards each other during both composite preparation and use.

(d) Preparation of and characterization of the behaviour of a wide variety of filament-matrix composites.

(e) Comparison of composite properties with the requirements of potential uses.

(f) Development of test and analysis methods by which suitable materials properties may be correlated with and used to predict component performance.



4 *Filament strength as a function of temperature*

Analysis of possible future uses for metal matrix composites will depend upon properties and behaviour which are attainable. These, in turn, can be varied very extensively as a result of the highly anisotropic contribution of the filaments to overall properties and the opportunity to control the geometry of filament location with respect to the external loading imposed on a structural component.

We shall outline first the possible directions of development interest for metal matrix composites followed by an analysis of the status of theory for, and experimental verification of their micromechanics. We shall then discuss and illustrate several topics of current experimental interest and present techniques and results in the characterization of some of the new filaments and the interactions which occur in metal matrices.

Potential for metal matrix composites

Analysis of the potential for future development and use of any new materials must be done within a framework of competition both with other possible materials and materials development routes, as well as with the variety of different ways in which a designer may use materials to perform a function. Initially, the properties of materials are compared. Eventually, of course, the cost-effectiveness of competing combinations of materials, fabrication processes and designs should dictate actual selection and use.

To correctly assess future potential, comparison should be with appropriate existing and possible future competition. Thus, a metal matrix composite for use at 600°F should be compared to titanium alloys, not aluminium, even if the matrix is aluminium. Further, the comparison should consider not only the materials themselves but also the most efficient ways of using materials; i.e., not only a sheet-stringer structure, but also a honeycomb structure of titanium when this would be more efficient.

Two points of view will now be defined for a discussion of future potential. One extreme considers metal bonded filaments, the other considers reinforced metals. Actual future development will, of course, involve considerations between these extremes, but knowledge of the behaviour of metal matrix composites is not yet sufficient to warrant a much more refined analysis. Consider first the metal bonded filament approach which focuses attention on the extreme strength or modulus to density ratios available in filaments, and attempts to devise ways of efficiently using these in lightweight structures. This might be considered a direct outgrowth of existing polymer bonded glass filament composite technology. The potential for metal bonded filaments is best evaluated by considering the reasons, if any, for a metal matrix rather than a polymer.

The most obvious potential advantage of a metal matrix is in resistance to long time exposure to many severe environments. Temperature will be used to illustrate; advantages in resistance to chemical attack and erosion, either singly or in combination with elevated temperature, are also probable. Fig. 4 shows the strength of some currently available filaments as a function of temperature. Very attractive strength retention suggests combination with appropriate matrices to provide high temperature composites. Specific comparisons will depend on the nature of the application, the loading, the time at temperature and other factors, but it is reasonable to assume that metal matrices may provide significant competition to polymer matrices at temperatures above about 250°F. Other possible advantages of metal matrices can be derived by considering some of the factors which currently prevent using the unidirectional strength to weight ratio of filaments as a direct indication of the weight of the

TABLE II Weight comparison of rocket motor cases (12)

Material	Strength, psi	Density, lb./in^3	Strength/Density, in.	Case weight, lb.
Steel Alloy	200×10^3	0·283	$0·71\times10^6$	536
Titanium Alloy	160 ,,	0·160	1·00 ,,	321
E. Glass Filament	350 ,,	0·092	3·81 ,,	301
S 994-Glass Filament	437 ,,	0·088	4·97 ,,	254

structural elements made from them and polymer matrices. Table II is derived from a recent study[5] into the optimization of polymer matrix-glass filament wound solid propellant rocket motor cases. For a specific application the weight of optimized filament wound cases is compared to that for cases fabricated from metals with the design allowables shown. Note that the enormous increase in strength-to-density ratio between the "homogeneous" metals and the filaments is not reflected in a comparable decrease in the weights of final cases. Some of the reasons for this are as follows:

(a) The composite is, of course, not 100% filament. These particular examples contained 18·8% weight % epoxy. Although the polymer matrix performs a necessary function in permitting the strength of the filaments to be utilized, it is generally assumed that it does not itself provide a significant addition to either the strength or elastic modulus of the composite.

(b) The filaments are assumed to be effective only along their axes. If the application involves a multiaxial stress field, additional filaments must be added to bear the load.

(c) Additional reinforcement must be added to the filament wound structures to cope with stiffness requirements and for cutouts, attachments, stress concentrations, i.e. at any point where stresses transverse to the filaments or shear loads occur or where the continuity of the filaments is disturbed or both.

In addition, a metal can offer very significantly greater tensile, shear and bearing strength as well as greater deformation prior to fracture than current polymer matrices. It can itself provide meaningful contribution to the elastic modulus of the composite in all directions. Also, if the mechanism by which the composite fractures involves a statistical accumulation of individual fiber breaks, a metal matrix may delay the onset of final catastrophic failure and thus increase the strength.

The reinforced metal approach focusses attention on the metallic matrix and the possibility of usefully improving its strength by the addition of filaments. In the extreme the addition of filaments might be considered to be comparable to any other strengthening mechanism such as cold working or precipitation hardening. This extreme would offer very real advantages. Existing technology for the reliable and effective design, fabrication and use of metals would be applicable, and new materials could find early acceptance and use. However, such an uncomplicated possibility is unlikely, and attention must be directed towards determining the nature and extent of differences between fiber reinforced and conventionally strengthened metals.

Finally, some comments relative to the use of various classes of filaments with metal matrices are appropriate. If appropriate strength or modulus to density ratios of the filaments alone are compared, metal wires are not attractive relative to glass, boron, silicon carbide, etc. filaments. High strength beryllium wires would be a singular exception. Thus, there is as yet little basis for the use of metal wires in the metal bonded filament approach. For reinforced metals, the ability of a metal wire to show plastic yielding, as contrasted to the essentially elastic behaviour of most other filaments, might be of some value in permitting deformation processing of the composite without unacceptable breakdown of the filaments, or in contributing to fatigue and impact resistance. Glass filaments do not have higher moduli than potential matrix metals such as aluminium or titanium. However, if the metal matrix is allowed to yield plastically, its effective modulus to use in determining the microstress distribution within the composite will by the tangent modulus and significant reinforcement by glass filaments can be demonstrated. The glass filaments may also influence crack propagation resistance.[6] Whether this implies advantages for glass, relative to the use of higher modulus filaments, is not yet clear.

High modulus filaments are currently of prime interest for use in reinforcing metals. Continuous filaments such as boron or silicon carbide will be applicable to either of the development approaches discussed above. Short filaments such as whiskers will initially be of interest primarily in a reinforcement approach. Higher volume percentages of such discontinuous filaments might also eventually be approached in a variety of ways such as forming a whisker-metal matrix wire for use in filament winding.

Micromechanics of metal matrix composites

Most of the past theoretical and experimental analysis of the mechanical behaviour of composites has been developed within the framework of polymer matrices. Some of these results are sufficiently general to apply to metal matrices in the low range of stress where both filament and matrix remain elastic. Beyond this range of stress a fundamental difference appears between metals and polymers. As the load increases, the elastic limit of the metal will be exceeded at local areas of high stress concentration and plastic flow will occur, accommodating the stress distribution at these locations. Further aspects of metal composite behaviour were aptly indicated by McDanels, Jech, and Wecton[3] in their delineation of the stages of deformation as: (a) elastic deformation of both filament and matrix, (b) elastic deformation of filament and plastic deformation of matrix, (c) plastic deformation of both filament and matrix, and (d) fracture.

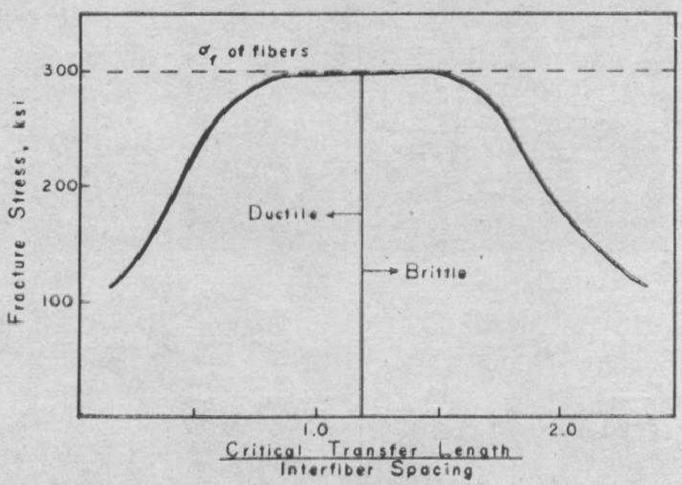
When one considers structural applications, there are a variety of properties which must be known before any designer will attempt to use any material. Tsai[7,8] has shown that in order to characterize the mechanical behaviour of a composite material one must know the longitudinal strength, modulus and Poisson's ratio, the transverse strength, modulus and Poisson's ratio, and the shear strength and modulus. Relationships between the elastic constants of the composite and those of the individual constituents have been developed by several workers.[7-16] In general, the ability to predict longitudinal strength and modulus under uniaxial tensile loads is fairly well advanced. Further work is needed to develop the ability to predict more accurately the transverse and shear strengths and moduli, and Poisson's ratio. All of these will include studies of the effects of such micromechanical variables as filament size, packing density, interfacial bond strength, and the materials properties of both constituents.

An exact analysis of the micromechanics of a composite containing discontinuous filaments such as whiskers or chopped fibres does not exist. Much of what is known has been summarized in recent reviews.[1,2,4] Indications are that the flow of stress or transfer of load in such a composite is along shear paths from the circumferential surface of one filament through the matrix to another filament. It is obvious that this mechanism is strongly influenced by the fibre-matrix interface.

The status of knowledge relating to creep and fatigue has been succintly indicated by Kelly and Davies[1]: "As yet there are no satisfactory analytical treatments which allow prediction of the creep and fatigue behaviour of fibre reinforced composites." This applies equally well to other structural design limiting parameters such as stress rupture, fracture toughness, ductility and yield strength. Some probing experimental efforts, notably those of Forsyth et al,[16] Baker and Cratchley,[6] and Parikh,[17,18] have been initiated in some of these areas. The effort of Forsyth and co-workers is aimed at improving creep, fatigue and crack propagation behaviour of aluminium rather than strengthening the metal. Results to date have shown that incorporation of stainless steel wires in aluminium sheets led to improved creep resistance and fatigue life.

The role of the interface in the mechanical behaviour of composites has yet to be treated satisfactorily but it has not been overlooked. Baker and Cratchley[6] in some early observations of silica reinforced aluminium under fatigue loading have indicated differences in behaviour between composites having weak and strong boundaries. Specimens which had strong interfaces showed better tensile behaviour than those with weak interfaces. The inverse was true for fatigue specimens, i.e. the weak interfaces gave better behaviour.

Recently Parikh[17] has been investigating the influence of critical transfer length, fiber diameter and interfiber spacing on the strength, deformation and fracture characteristics of metal wire-metal matrix composites. As shown in Figure 5, his preliminary results reveal that the ratio of the critical transfer length, as measured by pull-out tests, to the interfiber spacing affects both the tensile strength and the type of farcture.



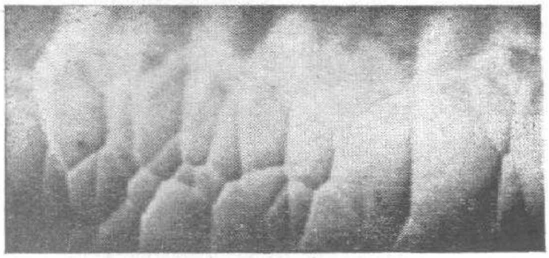
5 *Effect of critical transfer length and interfiber spacing on fracture and type of fracture in steel wire-lead solder composites (Parikh 17)*

A ductile or fiber "pull-out" type of fracture is characterized by failure in the matrix progressing along the composite. Brittle fracture is characterized by gross continuity in the filament and then proceeding across failure of the filaments, and hence the composite, in tension. Ductile fracture is accompanied by a high value of the work of fracture, and thus toughness; while the brittle fracture involves low fracture energy. Here one observes again preliminary indications of the important role of the filament-matrix interface, since one way of controlling the critical transfer length and thus the type of fracture is by controlling the nature of the interface.

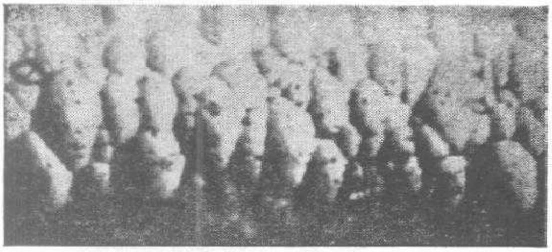
Filament characterization

Some of the methods we have developed for examining the filaments and measuring their mechanical properties will now be described. Observation of the fiber under the light microscope should be directed not only at the nature of the surfaces, Figure 6, but also to search for any fractures or fissures, Figure 7. Metallographic studies of cross sections and of sections parallel to the filament provide additional information. Our observations on boron filaments, grown by vapour deposition of boron on a tungsten wire substrate, may be selected as typical illustration of this procedure and of features for which to look.

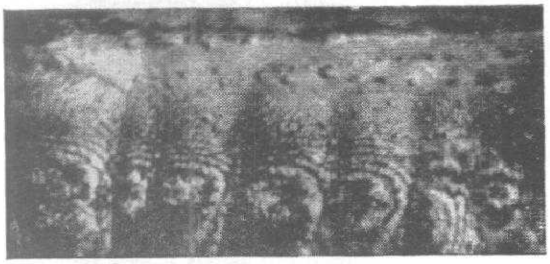
Optical surface observation of the as-received filament reveals both a "corn cob" structure, Figure 6 (a), and often contamination of the surface by oil films, grease and other substances, Figure 8. Further examination of the boron filament often reveals extended straight dark lines on the surface, Figure 9. When such a filament is cross sectioned, these can be identified as radially oriented cracks or fissures, Figure 7. Longitudinally sectioned specimens show the faces or walls of these fissures; since they do not exhibit



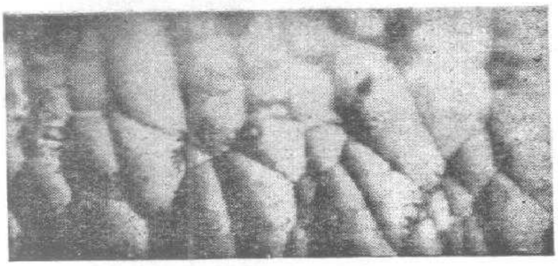
(a) Boron filament (Manufacturer A) ×1 000



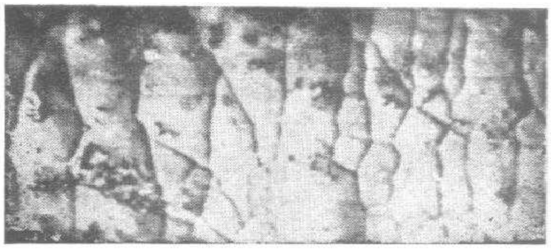
(b) Boron filament (Manufacturer B) ×1 000



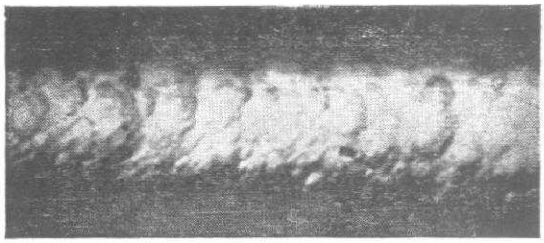
(c) Boron filament coating +SiC ×1 000



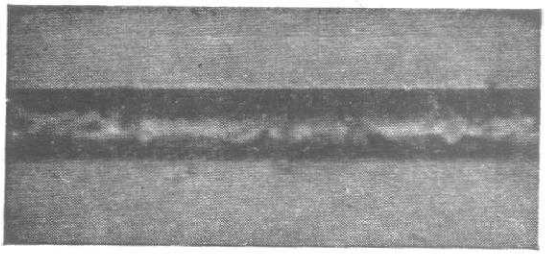
(d) Boron filament coating +Ti ×1 000



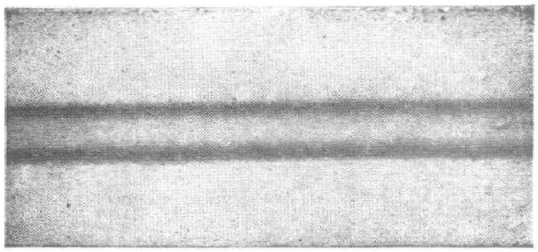
(e) Boron filament coating +TiN_2 ×1 000



(f) Silicon carbide filament ×1 000

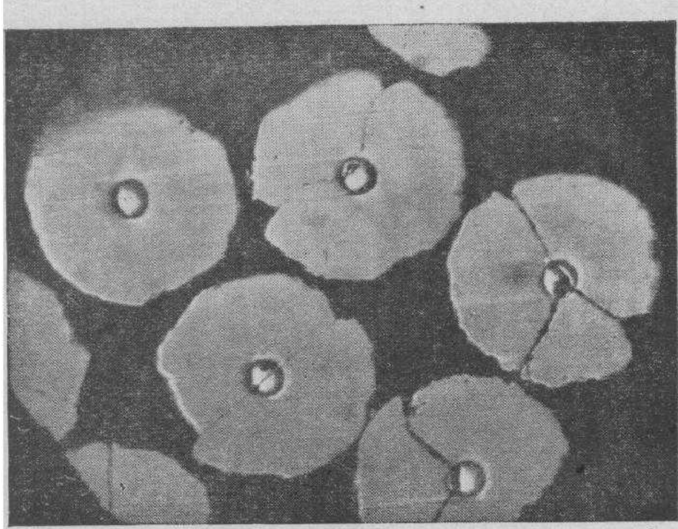


(g) Conventional glass filament with surface proctecting oil film ×1 000

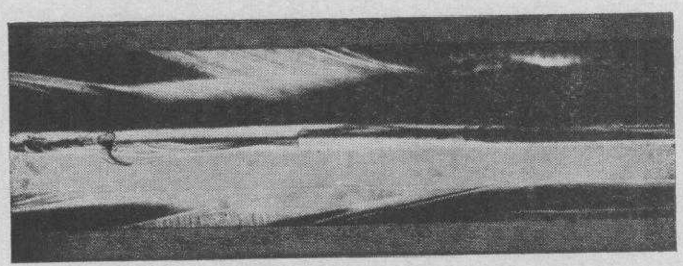


(h) Conventional glass filament clean surface ×1 100

6. *Various filaments with and without surface coatings*



7 *Cross sectioned filament with radial fissures* ×350

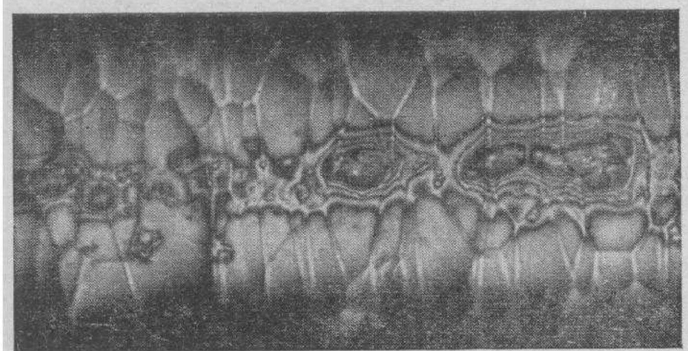


10 *View of longitudinal forced crack in a boron filament with conchoidal fracture lines* ×300

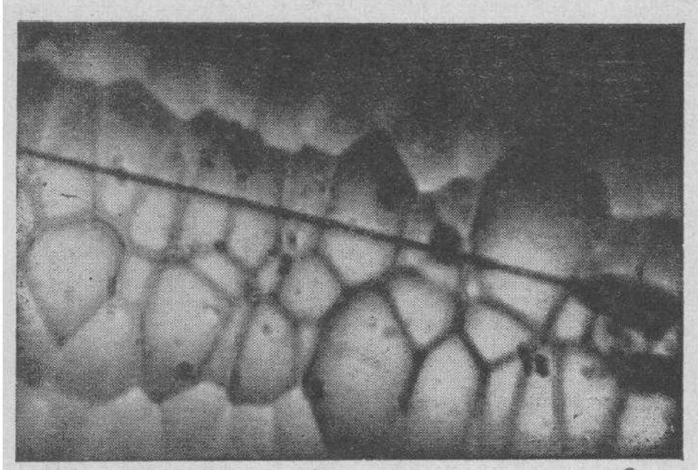
any conchoidal fracture lines as commonly seen on forcefully split filaments, Figure 10, the fissures probably occurred during vapour deposition of the boron.

In some instances these fissures cannot be observed by optical scanning since they are overgrown and thus self-sealed at the surface, Figure 11. If the fissures are open to the surface they may acquire contaminants by condensation of vapours or capillary adsorption of liquids. This is illustrated by the globules of liquid seen on the face of the fissure (after the filament was split) in Figure 12. Such contamination may interfere with effective filament-matrix bonding.

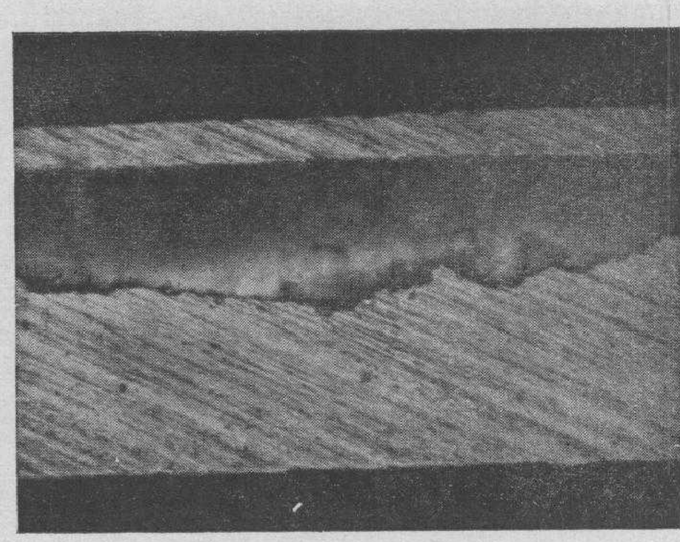
Since it is the mechanical properties of the filaments which initially generate interest in their use in composite, these properties should be carefully measured. The difficult case of a fine, short whisker and the measurement of its tensile strength and its modulus of elasticity will be considered. Testing of such a small specimen requires observation of several essential factors which are of vital importance for reliable data. These are: the centricity of load application, i.e., elimination of moments; the exact measurement of elongations for



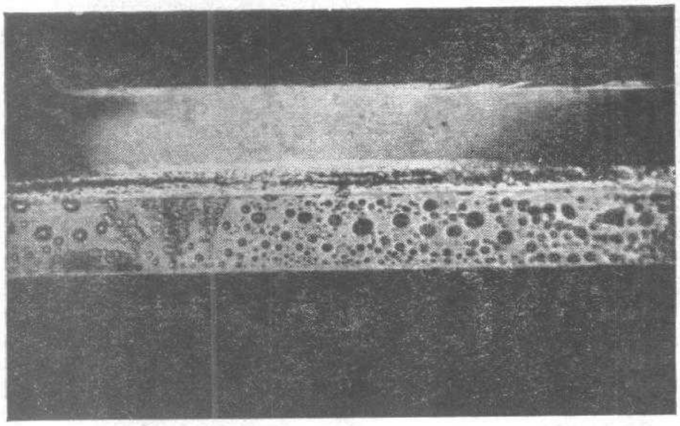
8 *Surface contamination with oil or grease films on boron filament* ×1 500



9 *Longitudinal fissure on the surface*

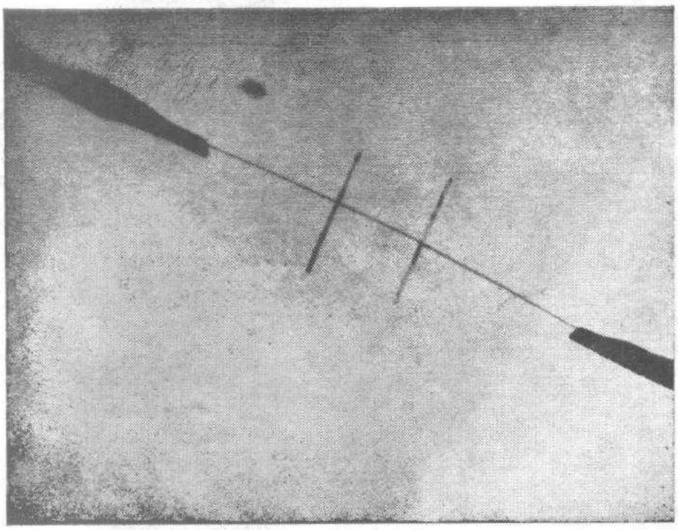


11 *View of the face of a fissure in a boron filament* ×800

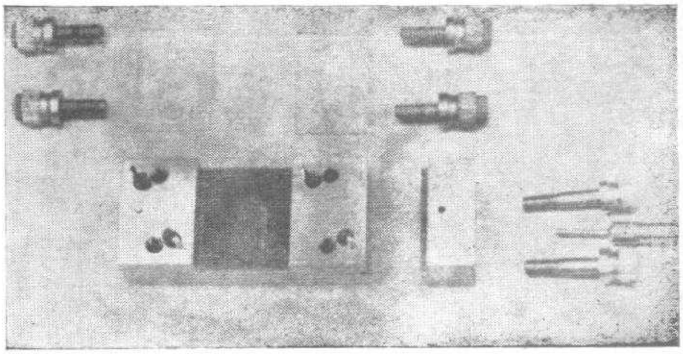


12 *View of the face of a fissure in the boron filament—one side self-sealed at the surface*

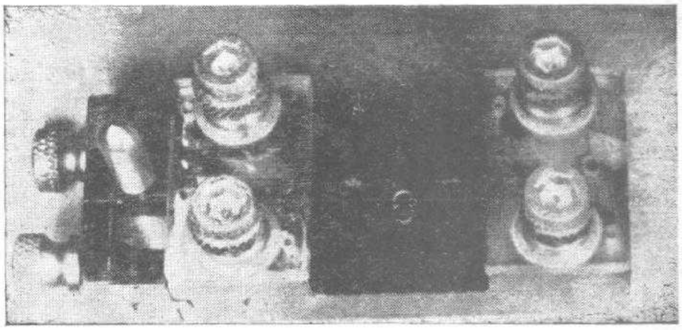
the determination of elastic behaviour ; the measurement of the cross sectional area. Equally important is the accuracy of measurement of load on the specimen during the test. For the sake of convenience, with fine short fibers or whiskers elongation is often measured as separation between the grips. However, this convenient approach often results in considerable error due to deformation which can occur in the cement in the grips. Therefore, it is often desirable to use some type of gage on the filament itself, and we have been cementing gage marks on the fiber specimen using micromanipulators, Figure 13. The gage marks are actually other whiskers and are cemented perpendicular to the fiber to be tested at a specific distance from each other. This distance is measured immediately before the tensile test of the specimen on a microscope. Wire loops are aligned between pins, one fixed and the other removable and clamped in a mounting block, Figure 14, and then the whisker specimen is placed on and cemented to the center of these loops. This approach with prealigned mounting blocks increases centricity of the small specimens in the tensile machine and eases the problems of handling and the danger of accidental damage until the test can be started. The images of the arc projected on a screen with the aid of an optical system consisting of a light bulb with a condenser lens and a high precision projection lens, Figure 15. These screens are



13 *Gage marks on whisker cemented to a wire loop* ×*15*

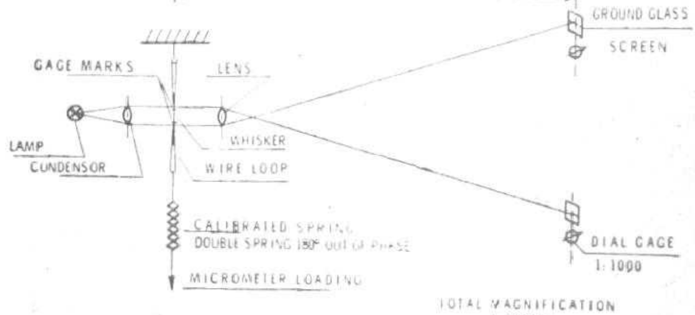


(*a*) *Exploded view*

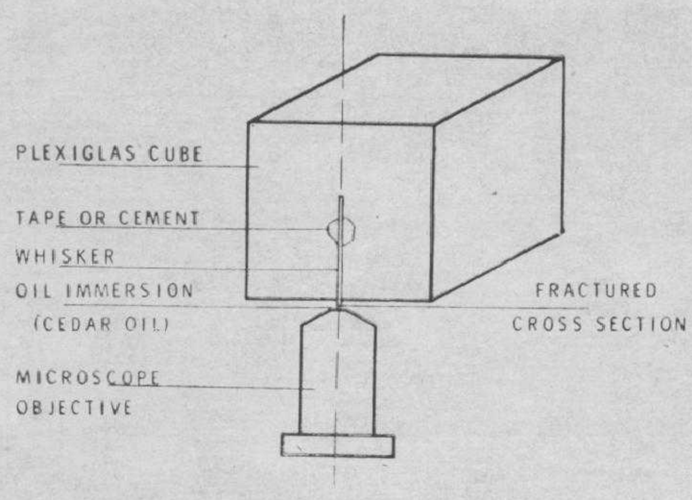


(*b*) *Assembled view with wire loops and whisker*

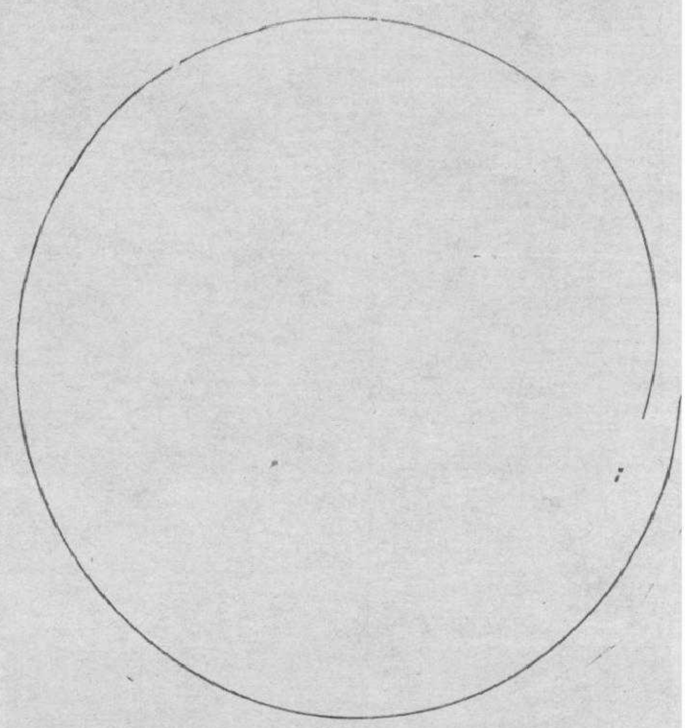
14 *Mounting block for whisker specimens*



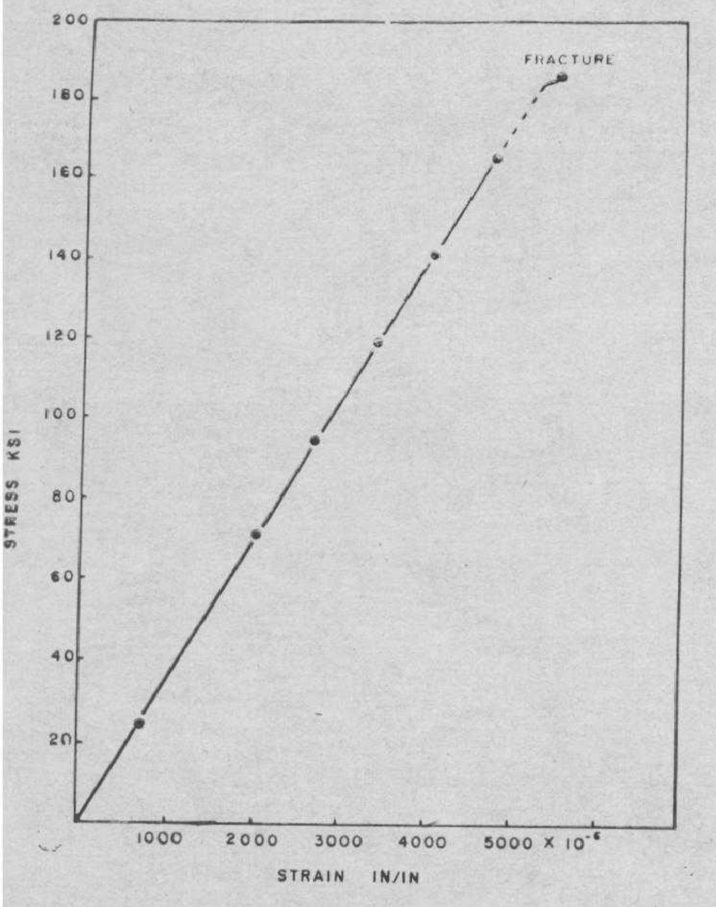
15 *Schematic diagram of the tensile tester*



16 *Arrangement of the fractured whisker for measurement of the area under the microscope (Schematic)*



18 *One half of a split and curled boron filament* ×*1*

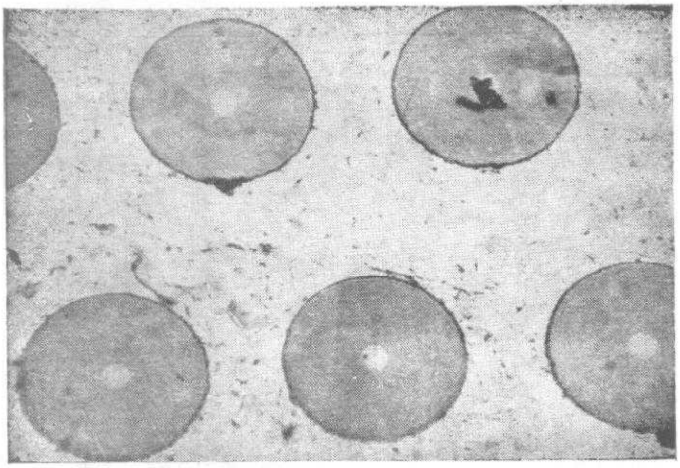


17 *Stress-strain curve of iron whisker as obtained on the whisker tensile tester (Cross section at fracture=3·3μ² used to calculate stress)*

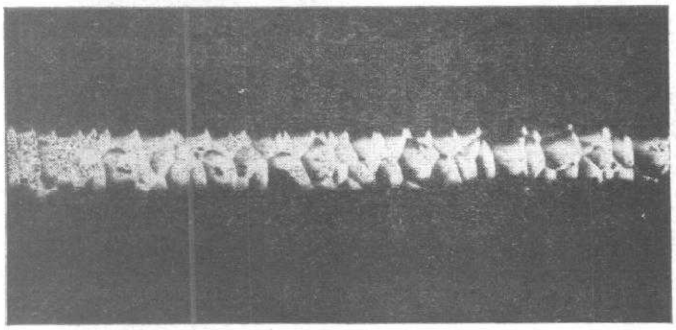
actually two inch square pieces of ground glass mounted on dial gages of 1 : 1000 at a distance of 200 inches from the lens. This provides an amplification factor of 1 : 200000[19].

After specimen fracture the wire loops with the fractured part of the specimen still attached are mounted on one side of a plexiglass block with scotch tape in such a manner that the specimen tip is protruding a few thousandths of an inch above the perpendicular face of the block, Figure 16. Then the specimen can be viewed from the side perpendicular to its axis.[20] Similarly by reorienting the block on the microscope stage with the specimen axis parallel to the microscope axis, the fracture area can be seen. The area can be measured with a micrometer eye piece which should be precisely calibrated for the exact optical magnification factor. After the strain readings are plotted and the area is determined, the strength and the elasticity modulus can be calculated, Figure 17.

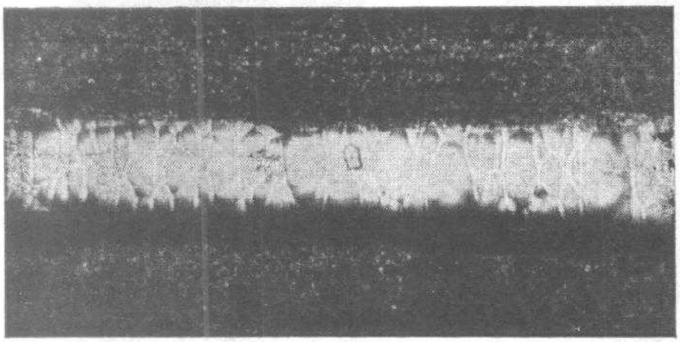
During handling it was observed that the boron filaments sometimes split when they are being cut to desired lengths. This indicates the presence of high residual stresses. In one instance, a foot long specimen of a boron filament split during cutting and the two halves curled up in nearly perfect cirlces, Figure 18. Once the splitting started, it progressed slowly but continuously until both parts were completely separated.



(a) Boron fibers embedded in a nickel matrix ×250

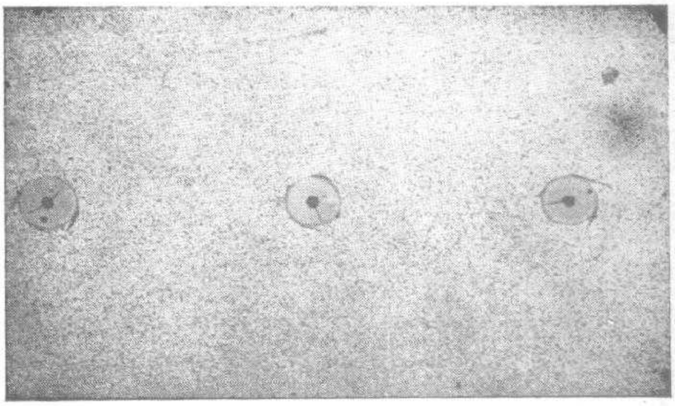


(b) Surface of boron filament ×340



(c) Surface of nickel matrix showing replication of boron surface ×340

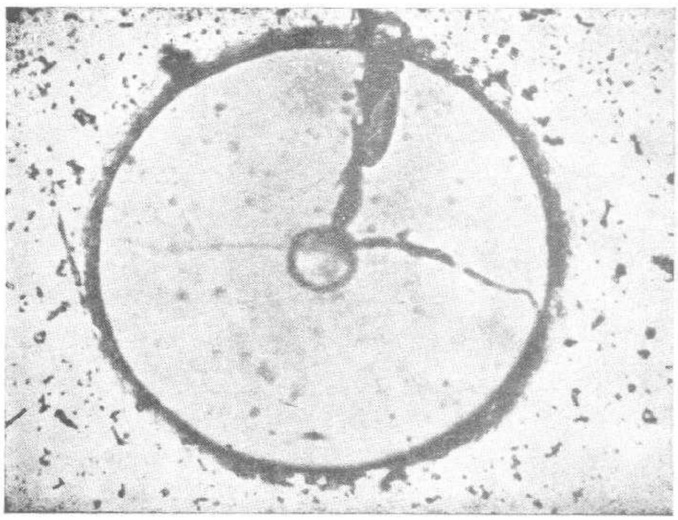
19 *Illustration of mechanical bond in a nickel-boron composite (Courtesy General Technologies Corporation)*



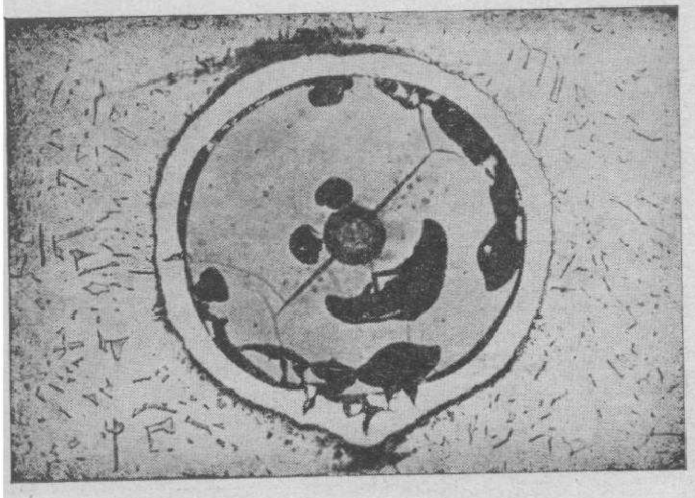
20 *Illustraton of metallurgical bond in a Ti-6Al-4V-Boron composite (Courtesy NAA/LAD)* ×100

Filament-matrix interactions

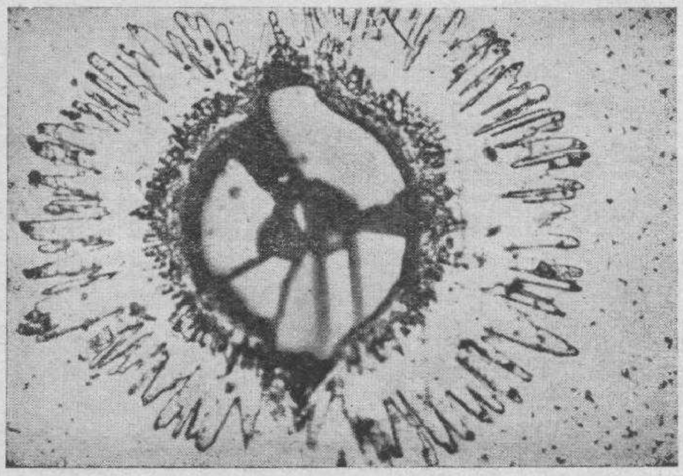
Two types of bond at the fiber matrix interface should be distinguished: mechanical and metallurgical. A mechanical bond is illustrated in Figure 19 by a nickel-boron composite fabricated by a molecular forming process by the General Technologies Corporation. Figure 19 (a) is a transverse section of the composite showing the filaments in a nickel matrix. Figure 19 (b) shows the characteristic "corn cob" stucture of the surface of a boron filament. Figure 19 (c) is a longitudinal section of the composite showing the surface of the nickel matrix from which a filament had been extracted leaving a replica of its surface. A metallurgical bond illustrated in Figure 20 by a Ti-6A1-4V boron filament



21 *Al-B Composite (Courtesy NAA/LAD)* ×500



22 *Ti-8Al-1V-1Mo-B composite after exposure at 1650°F for 60 hours*



24 *Fe-B Composite after exposure at 1650°F for 1 hour*

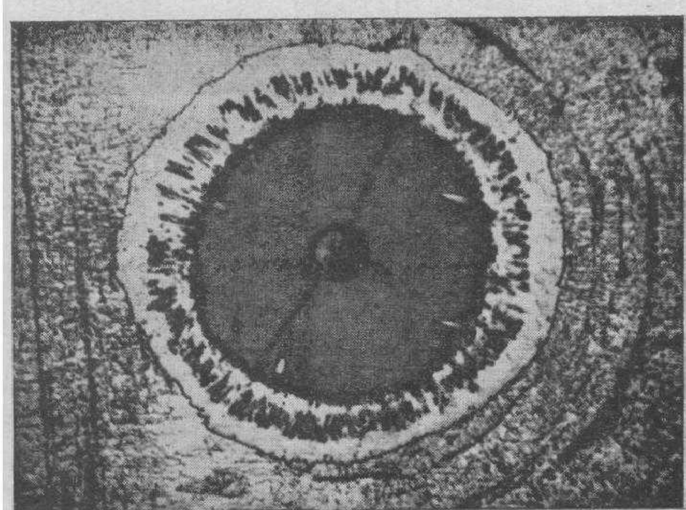
composite fabricated by the North American Aviation/Los Angeles Division. The compound titanium diboride forms at the interface between the boron filament and the alloy.

The following series of examples taken from work done at the AFML will illustrate briefly the types of reaction which may result between boron and various metal matrices.

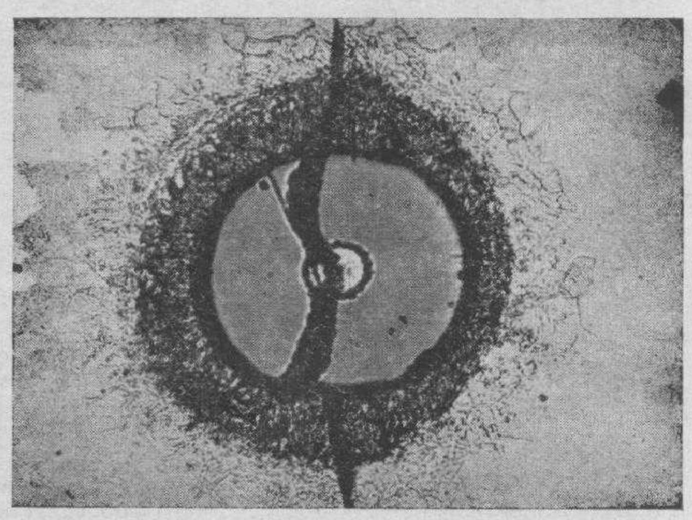
In an aluminium-boron composite fabricated by diffusion bonding there is no reaction evident at the interface, Figure 21. Simple compound formation was illustrated in Figure 20 while the growth of this phase after heat treatment is shown in Figure 22. Complex compound formation consisting of several phases is illustrated by a nickel-boron composite after heat treatment, Figure 23. A sunburst-like diffusion pattern is illustrated by the iron-boron filament interaction, Figure 24. An 18% Ni maraging steel-boron interaction is illustrated in Figure 25. It is entirely different than that of iron and thus qualitatively shows the effect of matrix alloying elements on the interaction behaviour. Eutectic formation and the resultant cast structure is illustrated in Figure 26 for a copper-boron composite.

Another type of interaction which may occur with composites containing boron filaments is the formation of a glass, as illustrated by an aluminium-boron composite, Figure 27, which was fabricated by powder metallurgy techniques.

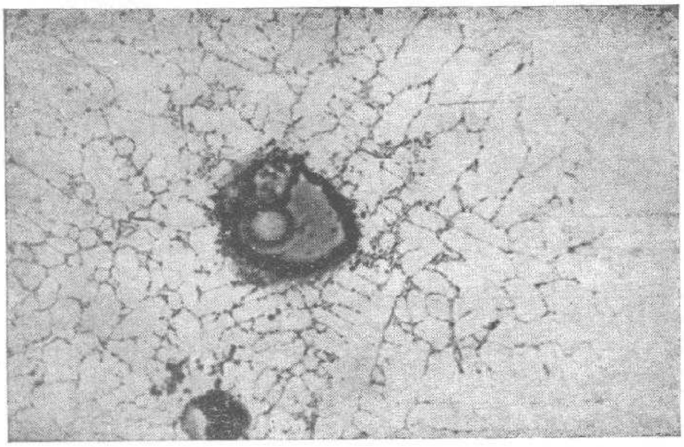
The illustrations certainly indicate that a variety of



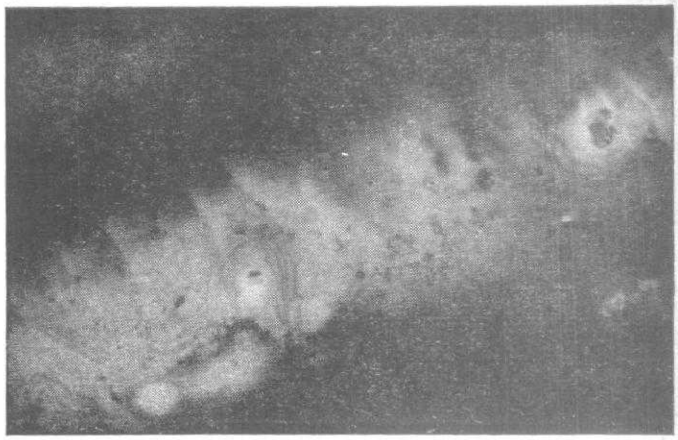
23 *Ni-B composite after exposure at 1380° F for 1 hour* ×500



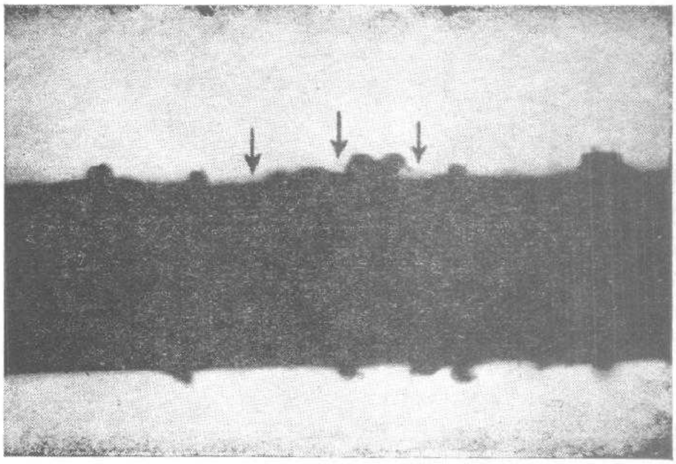
25 *Maraging steel (Fe-18Ni)—boron composite after exposure at 1650°F for 1 hour* ×500



26 *Cu-B Composite after synthesis* ×500



(*a*) *Reflected light* ×840



(*b*) *Transmitted light* ×280

27 *Al-B Composite showing glassy phase*

interactions may occur. Control of the interface will be vital, but the nature of this control is not yet established. Some of the more obvious possibilities are fiber coating, matrix alloying and the development of compatible fibre-matrix combinations. Regardless of the method or methods chosen, control of the interface is inherent for control of the mechanical properties.

Concluding remarks

Filament-metal metrix composite materials show significant potential for future development and use. However, much theoretical analysis and experimental verification of both micromechanics of composites and their behaviour under a variety of use conditions, and on the broad subject of filament-matrix interactions must yet be done to indicate the possible as well as the most feasible and attractive directions to follow. The acquisition of reliable experimental data, on reproducible specimens with well characterized structures, warrants priority attention.

The overall area of composite materials will demand unprecedented cooperation between activities such as structure-property relationships, laboratory preparation, production processing, materials testing and structural design and evaluation. In the extreme, a material and component might be "synthesized" to final shape for a specific application. New use concepts will be required to cope with the highly anisotropic contribution of the filaments to overall properties and to derive maximum benefit from the opportunity to control location geometry with respect to external loading. An iterative approach will be necessary, incorporating a significant amount of what we have called "vertical interdisciplinary" competence.[21]

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Discussions

Mr **L. J. Balasundaram,** (N.M.L.) : Is there any relationship between the mode of distribution of filaments in the matrix and the strength of the reinforced material, and if so how do you control it?

How does the filament reinforced materials compare with dispersion hardened materials?

Lt **W. F. Stuhrke,** (Author): In reply to your first question we were very interested in trying many approaches to control the distribution of these filaments in the metal matrix because obviously distribution is what determines the properties of the particular direction, the material being extremely anisotropic. We are trying a number of different methods ranging from diffusion technique, random alignment technique, etc.

Now about dispersion hardening there is a significant difference between these two materials. On dispersion hardening, size factor is somewhat smaller than one is interested in dislocation motion where as in these materials when a filament is 5/1000 of an inch which is many tens of thousands of an augstrom and speaks about stress interaction rather than dislocation interactions. We don't feel this results in any strengthening. We feel that there is really no such relationship. At the moment we stopped with circular filaments but we would like to try square ones; hollow ones; as a matter of fact the technology of distribution is not much advanced.