NASA TM-81591

NASA Technical Memorandum 81591

NASA-TM-81591 19810003661

Laminates and Reinforced Metals

C.C. Chamis
Lewis Research Center
Cleveland, Ohio

October 1980

NASA

LAMINATES AND REINFORCED METALS

by C. C. Chamis

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-570

ABSTRACT

A selective review is presented of the state-of-the-art of metallic laminates and fiber-reinforced metals called herein metallic matrix laminates (MMLs) for convenience. Design and analysis procedures that are used for, and typical structural components that have been made from MMLs are emphasized. Selected MMLs, constituent materials, typical material properties and fabrication procedures are briefly described, including hybrids and superhybrids. Advantages, disadvantages, and special considerations required during design, analysis and fabrication of MMLs are examined. Tabular and graphical data are included to illustrate key aspects of MMLs. Appropriate references are cited to make the article self-contained and to provide a selective bibliography of a rapidly expanding and very promising research and development field.

INTRODUCTION

There is a natural desire in the technical community to satisfy several diverse and competing design requirements in a cost-effective manner. Recently this desire has been affected by the need for energy conservation, due to energy shortages and increasing energy costs, and the need to develop cost-effective alternatives for critical materials. As a result, material scientists, structural designers/analysts, and fabricators have jointly conducted extensive research and development to the point where metallic laminates and fiber-reinforced metals are serious contenders for structural applications. In this report these laminates are called metallic matrix laminates (MMLs) for convenience. MMLs made with reinforcing fibers are relatively expensive at this time (1980) due to the cost of the fibers and fabrication procedures. However, the cost of MMLs will decrease as the volume increases. Until now they have been used mainly in aerospace structures. However, they will find more extensive use as energy efficiency and other design considerations, including scarcity of critical materials, override the material cost considerations.

A large body of information has been generated about MMLs over the last fifteen years. Significant developments of MMLs are reported in the Proceedings of the Society for the Advancement of Materials and Processing Engineering (SAMPE) as well as other technical publications. These proceedings include papers which are presented at the two SAMPE annual meetings in spring and fall. Three recently compiled bibliographies with abstracts (refs. 1, 2, and 3) cover technical articles and government reports that have been published since about 1965. Kreider (ref. 4) provides an extensive review of MMLS covering developments up to 1972. Boron-fiber-reinforced aluminum (boron/aluminum composites) and graphite-fiber-reinforced aluminum (graphite/aluminum composites) are reviewed in reference 5. The present article is a selective review of the state of the art of MMLs. The emphasis of the review is on design/analysis procedures and structural components that have been made from MMLs.

Specifically, the article includes discussion of (1) selected MMLs and definitions, (2) constituent materials, metals and fibers, for MMLs, (3) typical mechanical, thermal and physical properties of both constituents and MMLs, (4) fabrication procedures - brief description, (5) design/analysis procedures, (6) special types of metallic MMLs, (7) special types of fiber-reinforced MMLs, and (8) hybrids and superhybrids. The discussion is complemented with suitable tabular and graphical data, photographs of structural components that have been made, and appropriate references. The majority of the references cited deal with key aspects of reinforced MMLs and therefore, serve as a bibliography as well.

SELECTED LAMINATES AND DEFINITIONS

The types of MMLs that will be reviewed herein include those made from fiber-reinforced metals, superhybrids and those made from layers of different metals. Fiber-reinforced metals consist of unidirectional fiber composite (UFC) laminates, as depicted schematically in figure 1(a), and angleplied laminates (APL), figure 1(b). In both UFC and APL laminates, metallic foils may be used between plies to enhance certain mechanical properties as will be discussed later. Superhybrid composites (SHC) consist of outer metallic foils, boron/aluminum plies (B/Al), graphite-fiber/resin (UFC) inner or core plies, and adhesive film between these as shown in the photomicrograph in figure 1(c). Metallic laminates consist usually of alternate layers from different metals as depicted schematically in figure 1(d). The various procedures that are used to fabricate these laminates will be described later. The combinations of materials that are used to make these laminates are described below.

The basic unit used to study, design and fabricate UFC laminates is the single layer (ply, monolayer, lamina) which consists of stiff, strong fibers embedded in a metal matrix. The fibers and the matrix are generally called the constituent materials, or constituents, of the laminate (composite) in the composites community literature. Various constituents that have been used to make UFC are summarized alphabetically under the heading fiber reinforced metal laminates (first two columns in table 1). As can be seen in this table a large number of constituent materials are used for both fibers and matrices. The materials for fibers range from alumina to whisker. Those for matrices range from aluminum to superalloy. The constituents used thus far for SHC have been those summarized under superhybrids in table 1. The constituents that have been used for metallic laminates are summarized in the last two columns of table 1. An extensive list of constituent combinations for metallic laminates is tabulated in Kreider (ref. 4, page 40), and a list of constituent combinations for metallic laminates made by explosive bonding is also tabulated (ref. 4, page 49).

Mechanical and physical properties of constituent fiber reinforcements for MMLs are summarized in table 2. Part of the data in this table is from Rubin (ref. 6). That for the whiskers is from McCreight, et al. (ref. 7). Corresponding properties for metal matrices and metallic constituents for MMLs are summarized in table 3.

FABRICATION PROCEDURES - BRIEF DESCRIPTION

Metal matrix laminates (MMLs) are generally fabricated using diffusion bonding, roll-bonding, coextrusion, explosive bonding and brazing.

Several other fabrication methods are also used, depending on the type of constituent metal used in the laminate. These methods include: vacuum infiltration casting, high energy forming, flow molding, plasma spraying, hot pressing, continuous infiltration, powder metallurgy methods for discontinuous fiber composites, explosive welding and superplastic forming (Kreider (ref. 4) and Renton (ref. 5)).

In diffusion bonding, the filaments or the interleaf layers (plies) are hot pressed between layers of the matrix material. For example, for aluminum matrix laminates, the pressures usually range up to 20,000 psi and the temperature up to 2200° F. In roll-bonding, the layers in the metal/metal laminates are bonded by mill rolling under specified temperatures and pressures. In the case of fiber-reinforced metals, first, the ply (monolayer) is formed by diffusion bonding, or one of the other methods, and second, the laminate of the specified number of plies is made by roll-bonding or hot-pressing. In coextrusion, the constituents are assembled in a billet and are extruded through a given die at specified temperatures and pressures depending on the constituents used. The primary bonding mechanism in the coextrustion process is diffusion bonding. Coextrusion is particularly suited for round and rectangular shaped bar stock. In explosive bonding, the constituent metal plies are bonded into a laminate by the high pressure generated through explosive means. The amount of charge used is determined by the metallurgical bond required between the plies. This method is especially suitable for fabricating MMLs from metal plies with widely different melting temperatures. In brazing, bonding of the constituent metal plies into a laminate is accomplished by a third metal constituent (brazing foil) which acts as a wetting liquid-metal phase and which has a lower melting temperature than either of the constituent metals. The plies to be bonded are stacked into a laminate with brazing foils between them. The temperature is then raised to between the melting temperature of the brazing foils and the constituent plies, and appropriate pressure is applied. Upon solidification, the brazing foil bonds the adjacent constituent plies together into a laminate. The temperature for fabricating boron/aluminum plies is about 1100° F while the pressure is less than 200 psi.

Superhybrids are fabricated by adhesively bonding titanium or other metal outer plies over composite plies such as boron/aluminum plies and graphite-fiber/epoxy inner plies (core) and sometimes with a titanium or other metal ply at the center (Chamis, et al. (refs. 8 and 9)). The adhesive bond between the metallic plies and between the metallic and composite plies is provided by using epoxy adhesive film approximately 1 mil thick. The bonding process is accomplished under a specified pressure and temperature normally used for epoxy-matrix composites. For example, this process might be a 3-hour cure at a temperature of 300° F under a pressure of 100 psi. The same bonding process (fabrication procedure) is used to fabricate the nongraphitic superhybrids, the Tiber hybrids (titanium/beryllium) and the adhesively bonded metallic-ply laminates.

TYPICAL PHYSICAL, THERMAL AND MECHANICAL PROPERTIES

Typical physical and mechanical properties of fibrous MMLs that have been made are summarized in table 4. The last three entries in this table are superhybrid composites (fig. 1(c)) where the core is made from graphite fiber (GRAPHITIC) composite, S-glass fiber (S-GLASS) composite, or Kevlar fiber (KEVLAR) composite. It can be seen in table 4 that MMLs can be made with densities ranging from 0.065 to 0.270 $lb/in.^3$, longitudinal strengths ranging from 50 to 200 ksi, and longitudinal moduli ranging from 11 to 45 million $lb/in.^2$. It can also be seen in table 4 that fibrous MMLs have relatively low transverse (T) strengths ranging from about 5 to 75 ksi.

The transverse moduli range from 2 million $lb/in.^2$ for the superhybrid to 30 million $lb/in.^2$ for the SiC/Ti. The transverse properties for several fibrous MMLs listed in table 4 are not available. These properties as well as those of metallic laminates (fig. 1(d)), can be predicted approximately by the methods summarized in the section DESIGN/ANALYSIS PROCEDURES.

Mechanical, thermal and physical properties are used in selecting fibrous MMLs for possible use in structural components during the preliminary design phases. These properties are then verified by selective testing and are subsequently used in the detailed analysis and the final design phases.

DESIGN/ANALYSIS PROCEDURES

Designing structures with metal matrix laminates (MMLs) necessitates use of MMLs in structures and structural parts in a cost effective way. Design requirements for structures may be: maximum strength with light weight, long life service with minimum strength degradation, notch or other defect insensitivity with high stiffness, impact resistance with high stiffness, damage tolerance with high stiffness, and low manufacturing and maintainance cost.

Because building or fabricating large or complex structures frequently is a single, nonrepetitious operation, there may be no time or money to evaluate alternative design concepts by trial and success. Therefore, alternate design concepts for a specific case are evaluated on paper. The formal way to evaluate structural concepts with respect to given design requirements is by the use of structural analysis. Structural analysis includes a collection of mathematical models (equations). These equations describe the response of the structure to the anticipated loads which the structure will have to resist safely during its life time.

A general structural analysis model in equation form is given by

$$M\ddot{u} + C\dot{u} + Ku = F \qquad (1)$$

Equation (1) describes the structural response at any point in the structure in terms of acceleration ($\ddot{u}$), velocity ($\dot{u}$) and displacement (u) for a given mechanical and/or thermal load condition (F). The structure's geometric configuration and material are represented in equation (1) in terms of mass (M), damping (C), and stiffness (K). Equation (1) applies to simple and/or complex structures made from any material. In order to use equation (1) for a structure or structural part made from a given material, the property values in M, C, and K for this material must be known.

Procedures for using equation (1) for the analysis and/or design of structures made from composite laminates are extensively discussed by Chamis (refs. 10 and 11). Herein, we are concerned mainly with determining the MML properties for M, C, and K to be used in equation (1). We are also concerned with strength and thermal properties which are needed to evaluate and/or select MMLs for specified design requirements.

If the MML behaves like a general orthotropic solid (ref. 10, page 8), then physical, thermal and mechanical properties that are needed for structural analysis of MMLs (figs. 1(b) and 1(d)) include: density (ρ), heat capacity (H_c), three thermal heat conductivities (k with subscripts), three thermal expansion coefficients (α), three normal (Young's) moduli (E), three shear moduli (G), three Poisson's ratios (ν) and nine strengths (S). Except for ρ and H_c, the other properties are given with respect to three mutually orthogonal directions which are taken to coincide with the planes of elastic symmetry of the MML. These directions are 1, 2, and 3 in figure 1(a) and are referred to as the material axis of the single layer (ply). Or x, y, and z in figures 1(b) and 1(d) and are referred to as structural or load axis of the laminate (composite). It is customary to use subscripts to denote the directions along which the properties are given. The subscript l in combination with subscripts 1, 2, and 3 is used to denote ply material axis properties, while the subscript c in combination with subscripts x, y, and z is used to denote composite structural axis properties. For examples, $E_{\ell 11}$ denotes the modulus of elasticity (normal modulus) in the 1-direction and $G_{\ell 12}$ the shear modulus in the 1-2 plane (fig. 1(a)). The corresponding moduli along the structural axis of the MML (figs. 1(b) and 1(d) are E_{cxx} and G_{cxy}. These properties are summarized in symbolic form in table 5 for MMLs with three types of symmetry. As previously noted, the material axis properties are for the single layer (ply) while the structural axis properties are for the laminate (composite).

Theories have been developed, verified and are available for predicting material axis and/or structural axis properties based on constituent properties. These theories are included in the general field of composite mechanics (ref. 12). Composite mechanics is subdivided into micromechanics, macromechanics and laminate theory. Micromechanics embodies the various theories which are used to predict material axis properties of unidirectional fiber composites (plies) using constituent fiber and matrix properties. Typical results predicted for boron/aluminum plies using composite micromechanics are shown in figure 2. Macromechanics includes transformation equations which are used to transform material axis properties to other axis. Macromechanics also includes failure theories and failures criteria for plies subjected to combined stresses. Typical results predicted for boron/aluminum MMLs using composite macromechanics are shown in figure 3 for thermal and elastic properties and in figure 4 for strengths. Laminate theory embodies the equations and procedures which are used to predict the laminate properties using ply properties. Laminate theory is also used to generate the properties required to form the M, C, and K matrices (ref. 11, page 231; refs. 13 and 14). In addition, laminate theory is used to predict the lamination residual stresses in the plies. These residual stresses result from the difference between the processing and use temperatures as well as the difference between the thermal expansion coefficients of the constituents (refs. 15 and 16). Typical results predicted for boron/aluminum MMLs using laminate theory are shown in figure 5 for thermal expansion coefficients and elastic properties, and in figure 6 for lamination residual stresses. Lamination residual stresses (strains) affect significantly the laminate mechanical behavior of boron/aluminum MMLs (ref. 16). Different types of heat treatment also affect the mechanical behavior of MMLs, especially the transverse properties (ref. 5, page 72).

When MMLs are made from isotropic plies (fig. 1(d)), the analysis is considerably simpler as compared with that used for fiber composite plies. One such an analysis is described in detail in Chamis and Lark (ref. 17). Typical results obtained using this analysis are summarized in table 6 for titanium/beryllium (Tiber) hybrid MMLs.

The thermal and mechanical properties of MMLs as described previously constitute a minimum of the properties usually required to assess the suitability of a relatively new material at the preliminary design stage. Several other important factors need be considered simultaneously with the thermal and mechanical properties. Some of these factors are: fatigue resistance, creep, impact resistance, erosion and corrosion resistance, service environment effects, notch sensitivity and fracture toughness, damage tolerance and repairability, fabrication and quality control, reliability and durability, inspectability and maintainability, design data development costs and reproducibility, design/analysis experience of the staff and acceptance of the public agency which sets and administers structural integrity/safety requirements.

SPECIAL TYPES OF METAL/METAL LAMINATES

Special types of metal/metal MMLs that have been investigated include (table 1): (1) different plies of steels such as mild, high-strength and maraging, (2) aluminum/aluminum, (3) titanium/titanium and titanium/aluminum, (4) tungsten/superalloy and tungsten/tantalum, and (5) titanium/beryllium. One important reason for making and investigating these types of MMLs is their potential for fracture control and damage tolerance. Fracture control characteristics are usually assessed by using a material property called fracture toughness. The fracture toughness of a plate-form material, with a crack-like defect, is established by the stress that the material can resist prior to onset of rapid crack propagation. Fracture toughness is different for different materials. It is also different for the same generic material but with different alloying elements, thicknesses and heat treatments. In addition fracture toughness depends on temperature. In principle, then, by interleaving materials with different fracture toughnesses, the fracture toughness of MMLs can be altered and controlled within certain limits.

For analysis/design purposes, fracture toughness is used to determine the level of stress that a structural member with a given defect or crack size can safely support. This level of stress is usually determined using linear elastic fracture mechanics (LEFM). A basic equation from LEFM for a panel with a center-through-crack is the following

$$\sigma = \frac{K_c}{\sqrt{a}} F \qquad (2)$$

where σ is the average or gross stress (stress without the crack), K_c is the material fracture toughness parameter corresponding to the primary loading conditions and crack propagation directions depicted schematically in figure 7, a is the crack length; and F represents the stress state at the crack tip and depends on: (1) material, (2) geometry, and (3) loading condition. Values for K_c for different materials are found in reports published by the Metals and Ceramics Information Center (ref. 18) as well as in various handbooks dealing with aerospace structures and pressure vessel materials and design. The determination of F, on the other hand, generally requires complicated stress analyses which frequently are performed using finite element analysis.

The designer can use MMLs to control (prevent or limit) fracture, and thereby provide improved damage tolerance, in two ways: (1) using plies of materials with different fracture toughness to divide the fracture driving stress (crack divider), and (2) using plies with higher fracture toughness to arrest the fracture driving stress (crack arrest). Both of these are illustrated schematically in figure 8. In order for either concept to work, the type of bond has to be selected to meet three general criteria: (1) sufficiently strong to constrain the laminate to respond structurally (with respect to displacement, buckling and frequency) like a homogenous material, (2) sufficiently flexible to permit each ply to fracture independently of its neighbors, and (3) sufficiently brittle to fail by local delamination in the vicinity of the advancing crack front. Goolsby (ref. 19) discusses the fracture toughness of aluminum/aluminum MMLs fabricated by diffusion, roll, or explosive bonding while Koch (ref. 20) discusses those made by adhesive bonding. Photomicrographs depicting arrested cracks in actual samples are shown in Mileiko and Anishenkov (ref. 21). Oberson (ref. 22) provides a concise treatment of fracture analysis for aerospace metals while Miska (ref. 23) provides a comparable treatment for fatigue.

The root of a helicopter rotor blade is an example where MMLs are used for fracture control. This part of the blade may have crack-like defects because of the joint geometry and fabrication procedure as well as being subjected to high cycle fatigue. Wings of military aircraft and helicopter booms are potential applications for MMLs in order to provide damage tolerance for projectile impact.

In addition to providing fracture control or damage tolerance, MMLs are also used in applications where the interleaf may be the stronger, stiffer material while the primary material provides erosion, corrosion, oxidation or other service environmental resistance. Examples are tantalum/tungsten MMLs which are being investigated for possible use in aircraft engine turbine blades. Tantalum with a suitable coating is used to resist the corrosive environment of the burning fuel while tungsten is used for strength and stiffness in order to meet mechanical design requirements.

SPECIAL TYPES OF FIBER-REINFORCED METALS

Boron-fiber/aluminum-matrix (B/Al) MMLs have been made and investigated more extensively than those of any other fiber-reinforced metal. This type of laminate combines several of the desirable features of aluminum and, in addition, provides about a threefold improvement in modulus and about a sixfold improvement in strength over that of homogeneous aluminum. One disadvantage is the high cost of the boron fiber. And the major part of this cost is the tungsten substrate. In order to reduce the fiber cost, research has been done and development is underway to use carbon fiber for the substrate and/or to make larger diameter boron fibers.

Boron-fiber/aluminum-matrix MMLs have excellent fatigue, creep, corrosion and erosion resistance. Galvanic action may affect (degrade) the interfacial bond depending on the surface coating of the fiber. These MMLs have good temperature resistance up to about 300° F. They may be used with a relatively small property-loss penalty up to 600° F in stiffness-controlled designs such as dimensional stability, buckling and vibration frequencies. B/Al MMLs have improved fracture toughness compared to the aluminum matrix and are notch-insensitive. However, depending on the aluminum alloy and fabrication procedure, B/Al MMLs may have about one-half the impact resistance compared to aluminum. Christian and Adsit (ref. 5, pages 67 to 97) provide an extensive discussion on various mechanical properties of B/Al MMLs. The elevated temperature effects are discussed by Sullivan (ref. 24). Limited data available (Shramm and Kasen (ref. 25)) indicate that cryogenic temperature conditions have negligible effect on the tensile properties of B/Al MMLs.

Angleplied B/Al MMLs (fig. 1(b)) undergo inelastic deformations at relatively small load (about 10 to 20 percent of the fracture load) (ref. 26). In a cyclic load condition, these inelastic deformations may progressively improve or degrade or have no effect on the mechanical properties of the laminate (ref. 27). Conventional metal joining and repairing techniques are used for B/Al MMLs as well. Significant parameters affecting joints and joint designs are discussed by Janes (ref. 28).

Boron/aluminum MMLs have been made for a variety of structural components such as aircraft fuselage skins and stringers, aircraft wing skins, aircraft wing boxes, aircraft engine fan and compressor blades, propeller shells, landing gear struts, thrust support structures for the space shuttle, shafts for torque transmission, and rocket motor cases. Photographs of some of these structures are shown in figures 9 to 12. Miller and Robertson (ref. 5, pages 99 to 157) provide an extensive discussion on the application of B/Al MMLs for aerospace structures. Because of the high cost (about $250/lb in 1980 dollars) B/Al MMLs have not been considered seriously for use outside the aerospace industry as yet except in limited recreation applications such as tennis raquets and bicycle frames.

Graphite-fiber/aluminum-matrix (Gr/Al) MMLs are now being investigated mainly for B/Al MML replacement because of their low-cost potential (about 5 to 10 percent of B/Al MMLs). In addition, Gr/Al MMLs have excellent thermal dimensional stability. They may be suitable for use as superconductors because of their excellent thermal conductivity and good mechanical property retention at cryogenic temperatures. Gr/Al MMLs may also be suitable for friction-wear applications because of the inherent lubricating properties of the graphite fibers. However, Gr/Al MMLs are much more susceptible to galvanic action than are B/Al MMLs. Special surface treatment of the fibers is required to minimize this galvanic action. Gr/Al MMLs that have been made to date exhibit "rule-of-mixtures" properties along the fiber direction (table 4). However, the transverse properties are relatively poor. Alternatives such as heat-treating and metal-foil interleaving are used to improve the transverse properties. These alternatives are selected with considerable caution since they tend to degrade the longitudinal properties. Gr/Al MMLs have good fracture toughness and damage tolerance. They also have excellent mechanical and thermal fatigue resistance. Their corrosion and erosion resistance is comparable to that of B/Al. Pfeifer (ref. 5, pages 159 to 255) provides an extensive discussion and a good review of several important apsects of Gr/Al MMLs up to 1976.

Borsic-fiber/titanium-matrix and Borsic-fiber/aluminum-matrix MMLs have been investigated primarily for possible use in aircraft turbine engine fan blades. Borsic/titanium MMLs have about twice the stiffness and about 80 percent of the density of titanium (ref. 4, pages 269 to 318 and ref. 29). The combination of these two properties is generally sufficient to eliminate the midspan shrouds which are presently used to meet vibration and flutter design requirements.

Tungsten-fiber/superalloy (TF/SA) MMLs have been investigated for their potential use in aircraft turbine blades. The excellent mechanical property retention of the tungsten fibers at high temperatures (about 2000° F) is the key feature for investigating this type of laminate. However, TF/SA have two major disadvantages: (1) high density and (2) low cycle thermal fatigue degradation due to thermal expansion mismatch of the constituents. The high density disadvantage may be circumvented to some extent by appropriate structural design configurations, such as hollow blades. On the other hand, the low cycle thermal fatigue degradation can only be minimized by metallurgical considerations. Most of the research to date for TF/SA MMLs was conducted at laboratory level, Signorelli (ref. 30 and ref. 4, pages 229 to 267). Limited research has been initiated recently to make turbine blades from these laminates (refs. 31 and 32).

Whisker-reinforced metals and ceramic laminates also have been investigated for possible use in internal combustion engines and other high temperature applications. Disadvantages for these MMLs include the high cost of the whiskers and the problems associated with whisker matrix reaction which leads to poor interfacial bonding. Additionally, whisker-reinforced ceramic MMLs have poor fracture toughness and poor impact resistance characteristics. These poor characteristics may be improved by designing the laminate to operate in preferential compression.

Some of the other fiber-reinforced MMLs listed in table 4 have been investigated for specific applications. For example, graphite-fiber/magnesium-matrix MMLs were investigated for space antennas because of their desirable thermal distortion and low density properties, while graphite-fiber/lead-matrix MMLs were investigated for use in batteries where weight is an important design consideration. Some other MMLs listed in table 4 were investigated for metallurgical considerations at the fiber/matrix interface (borsic/aluminum, silicon carbide/aluminum). Still others have been or are being investigated at the laboratory level for scientific interest.

HYBRIDS

A general concensus definition for 'hybrid composite' may be summarized as follows: "A hybrid composite is that composite which combines two or more different types of fibers in the same matrix, or one fiber type in two different matrices or combinations of these (ref. 33, pages 1337 to 1339). Superhybrids (fig. 1(c)) are a generic class of composites which combine appropriate properties of fiber/metal-matrix composites, fiber/resin-matrix composites and/or metallic plies in a predetermined manner in order to meet competing and diverse design requirements (refs. 8 and 9). Tiber hybrids have been used by the author and his collegues as an acronym for titanium/beryllium adhesively bonded metallic laminates (ref. 17).

Boron-fiber-reinforced 1100, 2024, 5052, or 6061 aluminum alloys have been investigated for use in fan blades for aircraft turbine engines. Different diameter boron fibers (8 and 5.6 mil) may be included in the same hybrid. The high impact resistance of the 8-mil-diameter boron fiber in the 1100 aluminum alloy matrix (fig. 13) is combined with the high transverse tensile and shear properties of the 8- or 5.6-mil-diameter boron fiber in either 2024, 5052, or 6061 aluminum alloy matrix. Fan blades made from some of these hybrids and subjected to a small bird (3 oz starling) impact are shown in figure 14. The advantages and disadvantages of these types of hybrids are described by

McDanels and Signorelli (ref. 34) while their use for fan blades is described by Brantly and Stabrylla (ref. 35).

Superhybrids have been developed primarily for use in fan blades for aircraft turbine engines. This type of superhybrid generally has (1) longitudinal strength and stiffness comparable to advanced fiber composites, (2) transverse flexural strength comparable to titanium, (3) impact resistance comparable to aluminum, (4) transverse and shear stiffness comparable to aluminum, and (5) density comparable to glass-fiber/resin composites (ref. 8). In addition, superhybrids are notch-insensitive and are not degraded by thermal fatigue (ref. 9). Impact resistance data for superhybrids, other fiber composites, and some metals are summarized in table 7. The high-velocity impact resistance of superhybrid wedge-type cantilever specimens relative to other composites and titanium is shown in figure 15 (ref. 36). Large fan blades made by bonding a superhybrid shell over a titanium spar (either leading-edge or center) are shown in figure 16 (ref. 37).

Experimental data generated at Lewis Research Center showed that Tiber hybrids can be made which have: (1) moduli equal to that of steel, (2) tensile fracture stresses comparable to the yield strength of titanium, (3) flexural fracture stresses comparable to the ultimate strength of titanium, and (4) densities comparable to aluminum (ref. 17). The relatively high stiffnesses of Tiber hybrids and their relatively low densities compared to conventional metals make them good candidates for compression members in aircraft and space structures. Buckling stresses for plates and shells from Tiber hybrids are compared with those from advanced unidirectional composites and from conventional metals in table 8. As can be seen Tiber hybrids have superior buckling resistance compared to either other advanced composites or conventional metals. Another potential use for Tiber hybrids is in high-tip-speed fan bladés (fig. 17) for turbojet engines. Finite element analysis results showed that Tiber hybrid fan blades would have higher frequencies and lower tip distortions compared to those made from graphite fiber/resin composites (ref. 14). The comparisons for the first five frequencies for one fan blade design are summarized in table 9.

CONCLUSIONS

This article presents a selective review of the state-of-the-art of metallic laminates and fiber-reinforced metals, called herein metal matrix laminates (MMLs). Design/analysis procedures that are used for, and typical structural components that have been made from MML are emphasized. Specifically, the review covers the description of selected MMLs laminates, constituent materials and material properties, fabrication procedures, design/analysis procedures, special metallic and fiber-reinforced MMLs, hybrids and superhybrids, and structural components. The review shows that (1) the methodology is available to design and analyze structural components from MMLs, (2) the technology is available to fabricate structural components from these laminates and (3) a wide range of constituent metals and fibers, and lamination concepts for MMLs are available to meet diverse and competing design requirements. Though MMLs have several advantages with respect to structural design requirements, they also have different properties in different directions and have relatively high initial (residual) stresses. Both of these need special attention by the designer/analyst and the fabricator in designing and fabricating structural parts from MMLs.

REFERENCES

1. M. F. Smith, "Metal Matrix Composites," Vol. 2, NTIS/PS-78/0684, National Technical Information Service, Springfield, Va., 1978.
2. D. M. Cavagnaro, "Boron Reinforced Composites," Vol. 2, NTIS/PS-79/0476, National Technical Information Service, Springfield, Va., 1979.
3. D. M. Cavagnaro, "Boron Reinforced Composites," Vol. 2, NTIS/PS-78/0357, National Technical Information Service, Springfield, Va., 1978.
4. K. G. Kreider, ed., Metallic Matrix Composites, (Composite Materials, Vol. 4), Academic Press, New York, 1974.
5. W. J. Renton, ed., Hybrid and Select Metal Matrix Composites: A State-of-the-Art Review, American Institute of Aeronautics and Astronautics, New York, 1977.
6. L. Rubin, "Applications of Metal-Matrix Composites, the Emerging Structural Materials," in The Enigma of the Eighties: Environment, Economics, Energy, Nat. SAMPE Symp. Exhib., 24th., 1979, Book 2, pp. 1236-1249 (Science of Advanced Materials and Process Engineering Series, Vol. 24).
7. L. R. McCreight, H. W. Rauch, and W. H. Sutton, Ceramic and Graphite Fibers and Whiskers, Academic Press, New York, 1965.
8. C. C. Chamis, R. F. Lark, and T. L. Sullivan, "Boron/Aluminum-Graphite/Resin Advanced Composite Hybrids," NASA TN D-7879, 1975.
9. C. C. Chamis, R. F. Lark, and T. L. Sullivan, "Super-Hybrid Composites - an Emerging Structural Material," NASA TM X-71836, 1975.
10. C. C. Chamis, ed., Structural Design and Analysis, Part I (Composite Materials Series, Vol. 7), Academic Press, New York, 1974.
11. C. C. Chamis, ed., Structural Design and Analysis, Part II (Composite Materials Series, Vol. 8), Academic Press, New York, 1975.

12. C. C. Chamis, "Characterization and Design Mechanics for Fiber-Reinforced Metals," NASA TN D-5784, 1970.

13. C. C. Chamis, Comput. Struct., 3 (3), 467 (1973).

14. C. C. Chamis, J. Aircraft, 14 (7), 644 (1977).

15. C. C. Chamis, "Lamination Residual Stresses in Multilayered Fiber Composites," NASA TN D-6146, 1971.

16. C. C. Chamis, "Residual Stresses in Angleplied Laminates and Their Effects on Laminate Behavior," NASA TM-78835, 1978.

17. C. C. Chamis and R. F. Lark, "Titanium/Beryllirim Laminates: Fabrication Mechanical Properties, and Potential Aerospace Applications," NASA TM-73891, 1978.

18. Metals and Ceramics Information Center, 505 King Ave., Columbus, OH, 43201.

19. R. D. Goolsby, "Fracture of Crack Divider Al/Al Laminates," in ICCM2, Proceedings of the 1978 International Conference on Composite Materials, AIME, Warrendale, Pennsylvania, 1978, pp. 941-960.

20. G. H. Koch, "The Fracture Behavior of Multiply Layer Adhesive Bonded Aluminum Structures," in The Enigma of the Eighties: Environment, Economics, Energy, Nat. SAMPE Symp. Exhib., 24th., 1979, Book 1, pp. 649-658 (Science of Advanced Materials and Process Engineering Series, Vol. 24).

21. S. T. Mileiko and V. M. Anishenkov, "On Fatigue of Metal Matrix Composites," in The Enigma of the Eighties: Environment, Economics, Energy, Nat. SAMPE Symp. Exhib., 24th., Book 1, 1979, pp. 799-811 (Science of Advanced Materials and Process Engineering Series, Vol. 24).

22. H. J. Oberson, Jr., SAMPE J., 13, 4-11, November/December (1977).

23. K. H. Miska, Mater. Eng., 87 (6), 31-33 (1978).

24. P. G. Sullivan, "Elevated Temperature Properties of Boron/Aluminum Composites," NASA CR-159445, 1978.

25. R. E. Schramm and M. B. Kasen, "Static Tensile Properties of Boron-Aluminum and Boron-Epoxy Composites at Cryogenic Temperatures," in K. D. Timmerhaus, R. P. Reed, and A. F. Clark, eds., Advances in Cryogenic Engineering, Vol. 22, Plenum Press, New York, 1977, pp. 205-213.

26. C. C. Chamis and T. L. Sullivan, "A Computational Procedure to Analyze Metal Matrix Laminates with Nonlinear Lamination Residual Strains," NASA TM X-71543, 1974.

27. C. C. Chamis and T. L. Sullivan, "Nonlinear Response of Boron/Aluminum Angleplied Laminates Under Cyclic Tensile Loading: Contributing Mechanisms and Their Effects," NASA TM X-71490, 1973.

28. S. Janes, "Application of Conventional Joining Techniques to Boron Fiber and Carbon Fiber Reinforced Aluminum," Battelle Institute, Frankfurt, West Germany, Report D2532 HI, 1976.

29. B. R. Collins, W. D. Brentnall, I. J. Toth, "Properties and Fracture Modes of Borsic Titanium," AFML-TR-73-43, 1972.

30. R. A. Signorelli, "Review of Status and Potential of Tungsten-Wire-Superalloy Composites for Advanced Gas Turbine Engine Blades," NASA TM X-2599, 1972.

31. W. D. Brentnall, "FRS Composites for Advanced Gas Turbine Engine Components," TRW, Inc., Cleveland, Ohio, Report TRW-ER-7887-F, AD-A050 595, 1977.

32. D. W. Petrasek, E. A. Winsa, L. J. Westfall, and R. A. Signorelli, "Tungsten Fiber Reinforced FeCrAlY - A First Generation Composite Turbine Blade Material," NASA TM-79094, 1979.

33. B. R. Noton, et al., eds., ICCM2, Proceedings of the 1978 International Conference on Composite Materials, AIME, Warrendale, Pennsylvania, 1978.

34. L. McDanels and R. A. Signorelli, "Effect of Fiber Diameter and Matrix Alloys on Impact Resistant Boron/Aluminum Composites," NASA TN D-8204, 1976.

35. J. W. Brantly and R. G. Stabrylla, "Fabrication of J79 Boron/Aluminum, Blades," General Electric Co., Cincinnati, Ohio, Report R79AEG388, 1979. (NASA CR-159566.)

36. R. C. Novak, "Multi-Fiber Composites," United Technologies Research Center, Hartford, Connecticut, Report R76-912098-11, 1976. (NASA CR-135062.)

37. C. T. Salemme and G. C. Murphy, "Metal Spar/Superhybrid Shell Composite Fan Blades," NASA CR-159594, 1979.

TABLE 1. - CONSTITUENT MATERIALS FOR METALLIC MATRIX LAMINATES

Fiber-reinforced metal laminates		Superhybrids					Metal/metal laminates	
Fiber	Metal	Metal matrix composite		Resin matrix composite		Metal foil	Primary	Interleaf
		Fiber	Matrix	Fiber	Matrix			
FP alumina	Aluminum	Boron	Aluminum	Graphite	Epoxy	Titanium	Aluminum	Aluminum
	Lead				Polyimide			
	Magnesium						Beryllium	Titanium
Beryllium	Titanium			Kevlar	Epoxy			
Boron	Aluminum						Steel	Steel
	Magnesium			S-glass	Epoxy			
	Titanium						Titanium	Aluminum
								Titanium
Borsic	Aluminum							
	Titanium						Tungsten	Copper
								Superalloy
Graphite	Aluminum							
	Columbium						Tungsten	Tantalum
	Copper							
	Lead							
	Magnesium							
	Nickel							
	Tin							
	Zinc							
Molybdenum	Superalloy							
Silicon carbide	Aluminum							
	Superalloy							
	Titanium							
Steel	Aluminum							
	Nickel							
Tantanlum	Superalloy							
Tungsten	Columbium							
	Superalloy							
Whisker	Aluminum							
	Superalloy							

TABLE 2. - TYPICAL PROPERTIES OF CONSTITUTENT FIBER REINFORCEMENTS FOR METALLIC MATRIX LAMINATES (ALONG FIBER)[a]

Fiber	Density, lb/in.^{3}	Melting temperature, °F	Heat capacity[b]	Thermal condition[c]	Thermal expansion coefficient[d]	Tensile strength, ksi	Modulus, msi	Fiber diameter, mils	Remarks
Boron on tungsten	0.090	3810	0.31	22	2.8	525	58	4 to 8	Monofilament
Borsic	.098	3810	.31	22	2.8	450	58	4 to 6	Monofilament
Boron on carbon	.080	3810	.31	22	2.8	500	52	4 to 6	Monofilament
Graphite									
Pan HM	.067	6600	.17	580	-.6	320	55	.28	10 000 filaments per tow
Pan HTS(T300)	.063					340	30	.30	3000 filaments per yarn
Rayon(T50)	.060					315	57	.24	1440 filaments per 2-ply yarn
Thornel 75(T75)	.066					385	76	.21	1440 filaments per 2-ply yarn
Pitch (Type P)	.072					200	50	.2 to .4	2000 filaments per yarn
Pitch UHM	.074					350	100	.44	2000 filaments per yarn
Silicon carbide on tungsten	.120	4870	.29	9	2.4	450	62	4 to 6	Monofilament
Silicon carbide on carbon	.110	4870	.29	9	2.4	500	58	4	Monofilament
Beryllium	.067	2340	.45	87	6.4	140	42	5	Monofilament
FP alumina	.143	3700			4.6	220	55	.8	210 filaments per yarn
S-glass	.090	1540	.17	7.5	2.8	600	12	.35	1000 filaments per strand
E-glass	.090	1540	.17	7.5	2.8	400	10	.35	1000 filaments per strand
Molybdenum	.370	4750	.06	84	2.7	95	47	5	Monofilament
Steel	.280	2550	.11	17	7.4	300	30	5	Monofilament
Tantalum	.610	5420	.04	32	3.6	220	27	20	Monofilament
Tungsten	.700	6150	.03	97	2.5	460	57	15	Monofilament
Whisker									
-Ceramic (Al_2O_3)	.143	3700	.14	14	4.3	6200	65	.4 to 1	----------------------------
-Metallic (Fe)	.280	2800	.11	17	7.4	1900	29	5	----------------------------

[a]Most information from L. Rubin, 1979.
[b]Btu/lb/°F.
[c]Btu/hr/sq ft/°F/ft.
[d]μin./in./°F.

TABLE 3. - TYPICAL PROPERTIES OF METAL MATRICES AND METALLIC CONSTITUENTS FOR METALLIC MATRIX LAMINATES

Metal	Density, $in/in.^3$	Melting temperature, °F	Heat capacity[a]	Thermal conductivity[b]	Thermal expansion coefficient[c]	Tensile strength, ksi	Modulus, msi	Remarks[d]
Aluminum	0.10	1080	0.23	99	13.0	45	10	6061(T6)
Beryllium	.07	2340	.45	87	6.4	90	42	Annealed
Columbium	.31	4470	.06	32	3.8	40	15	----------
Copper	.32	1980	.09	226	9.8	50	17	Oxygen free hardened
Lead	.41	600	.03	19	16.0	3	2	1% Sb
Magnesium	.06	1050	.24	44	14.0	40	6	AZ31B-H24
Nickel	.32	2620	.11	36	7.4	110	30	Nickel 200 hardened
Steel	.28	2660	.11	17	7.4	300	30	Ultra high strength (mod.H-11)
Superalloy	.30	2540	.10	11	9.3	160	31	Inconel X-750
Tantalum	.60	5420	.04	32	3.6	60	27	----------
Tin	.26	450	.05	37	13.0	2	6	Grade
Titanium	.16	3000	.14	4	5.3	170	16	Ti-6Al-4V
Tungsten	.70	6170	.03	97	2.5	220	57	----------
Zinc	.24	730	.10	65	15.2	41	10	Alloy Agada

[a]Btu/lb/°F.
[b]Btu/hr/sq ft/°F/ft.
[c]μin./in./°F.
[d]Materials engineering material selector issue.

TABLE 4. - TYPICAL PHYSICAL AND MECHANICAL PROPERTIES OF METALLIC MATRIX COMPOSITES

Fiber	Matrix	Reinforcement, vol %	Density, lb/in.^{3}	Longitudinal		Transverse	
				Tensile strength, ksi	Modulus, msi	Tensile strength, ksi	Modulus, msi
G T 50	201 Al	30	0.086	90	24	7	5
G T 50	201 Al	49	-----	163	23	-----	---
G GY 70	201 Al	34	.086	95	30	4.5	5
G GY 70	201 Al	30	.088	80	23	10	6
G HM pitch	6061 Al	41	.088	90	47	-----	---
G HM pitch	AZ31 Mg	38	.066	74	43	-----	---
B on W, 5.6-mil fiber	6061 Al	50	.090	200	34	20	23
Borsic	Ti	45	.133	184	32.5	67	27
G T 75	Pb	41	.270	104	29	-----	---
G T 75	Cu	39	.220	142	35	-----	---
FP	201 Al	50	.130	170	31	(20)	20
SiC	6061 Al	50	.106	215	33	(20)	20
SiC	Ti	35	.142	175	38	75	30
SiC whisker	Al	20	.101	50	15	50	15
B_4C on B	Ti	38	.135	215	33	>50	>20
G T 75	Mg	42	.065	65	27	-----	---
G HM	Pb	35	.280	72	17	-----	---
G T 75	Al-7%Z	38	.087	126	28	-----	---
G T 75	Zinc	35	.191	111	17	-----	---
G T 50	Ni	50	.190	115	35	-----	---
G T 75	Ni	50	.193	120	45	5	6
G (3.2 mil)	2024 Al	50	.088	110	20	-----	---
G (5.6 mil)	2024 Al	60	.088	160	26	-----	---
Superhybrid	Graphitic	↓	.074	125	18	32	9
Superhybrid	S-glass		.078	107	11	28	4
Superhybrid	Kevlar		.065	102	12	28	2

TABLE 5. - PHYSICAL, THERMAL AND MECHANICAL PROPERTY SYMBOLS FOR PARTICULAR METALLIC MATRIX LAMINATES[a]

Property	Composite with type of symmetry of				Isotropic/axes	
	Generally orthotropic/axes		Transversely isotropic/axes		Ply	Composite
	Ply	Composite	Ply	Composite		
Density	ρ_ℓ	ρ_c	ρ_ℓ	ρ_c	ρ_ℓ	ρ_c
Heat capacity	$H_{c\ell}$	H_{cc}	$H_{c\ell}$	H_{cc}	H_c	H_{cc}
Thermal heat conductivity	$K_{\ell 11}$	K_{cxx}	$K_{\ell 11}$	K_{cxx}	K_ℓ	K_{cxx}
	$K_{\ell 22}$	K_{cyy}	$K_{\ell 22}$	K_{cyy}	K_ℓ	$K_{cyy} = K_{cxx}$
	$K_{\ell 33}$	K_{czz}	$K_{\ell 33} = K_{\ell 22}$	K_{czz}	k_ℓ	K_{czz}
Thermal expansion coefficient	$\alpha_{\ell 11}$	α_{cxx}	$\alpha_{\ell 11}$	α_{cxx}	α_ℓ	α_{cxx}
	$\alpha_{\ell 22}$	α_{cyy}	$\alpha_{\ell 22}$	α_{cyy}	α_ℓ	$\alpha_{cyy} = \alpha_{cxx}$
	$\alpha_{\ell 33}$	α_{czz}	$\alpha_{\ell 33} = \alpha_{\ell 22}$	α_{czz}	α_ℓ	α_{czz}
Elastic and shear moduli	$E_{\ell 11}$	E_{cxx}	$E_{\ell 11}$	E_{cxx}	E_ℓ	E_{cxx}
	$E_{\ell 22}$	E_{cyy}	$E_{\ell 22}$	E_{cyy}	E_ℓ	$E_{cyy} = E_{cxx}$
	$E_{\ell 33}$	E_{czz}	$E_{\ell 33} = E_{\ell 22}$	E_{czz}	E_ℓ	E_{czz}
	$G_{\ell 12}$	G_{cxy}	$G_{\ell 12}$	G_{cxy}	$G_\ell = \frac{E_\ell}{2(1 + \nu_\ell)}$	$G_{cxy} = \frac{E_{cxx}}{2(1 + \nu_{czy})}$
	$G_{\ell 23}$	G_{cyz}	$G_{\ell 23} = \frac{E_{\ell 22}}{2(1 + \nu_{\ell 23})}$	G_{cyz}	$G_\ell = \frac{E_\ell}{2(1 + \nu_\ell)}$	G_{cyz}
	$G_{\ell 13}$	G_{cxz}	$G_{\ell 13} = G_{\ell 12}$	G_{cxz}	$G_\ell = \frac{E_\ell}{2(1 + \nu_\ell)}$	$G_{cxz} = G_{cyz}$
Poisson's ratios	$\nu_{\ell 12}$	ν_{cxy}	$\nu_{\ell 11}$	ν_{cxy}	ν_ℓ	ν_{cxy}
	$\nu_{\ell 23}$	ν_{cyz}	$\nu_{\ell 23}$	ν_{cyz}	ν_ℓ	ν_{cyz}
	$\nu_{\ell 13}$	ν_{cxz}	$\nu_{\ell 13} = \nu_{\ell 12}$	ν_{cxz}	ν_ℓ	$\nu_{cxz} = \nu_{cyz}$
Strengths[b]	$S_{\ell 11T,C}$	$S_{cxxT,C}$	$S_{\ell 11T,C}$	$S_{cxxT,C}$	$S_{\ell T,C}$	$S_{cxxT,C}$
	$S_{\ell 22T,C}$	$S_{cyyT,C}$	$S_{\ell 22T,C}$	$S_{cyyT,C}$	$S_{\ell T,C}$	$S_{cyyT,C} = S_{cxxT,C}$
	$S_{\ell 33T,C}$	$S_{czzT,C}$	$S_{\ell 33T,C} = S_{\ell 22T,C}$	$S_{czzT,C}$	$S_{\ell T,C}$	$S_{czzT,C}$
	$S_{\ell 12S}$	S_{cxyS}	$S_{\ell 12S}$	S_{cxy}	$S_{\ell S}$	S_{cxyS}
	$S_{\ell 23S}$	S_{cyzS}	$S_{\ell 23S}$	S_{cyz}	$S_{\ell S}$	S_{cyzS}
	$S_{\ell 13S}$	S_{cxzS}	$S_{\ell 13S} = S_{\ell 12S}$	S_{cxz}	$S_{\ell S}$	$S_{cxzS} = S_{cyzS}$

[a]Subscripts refer to directions shown in fig. 1.
[b]T = tension
C = compression
S = shear.

TABLE 6. - COMPARISON OF MEASURED AND PREDICTED PROPERTIES OF TIBER LAMINATES

Property identification	Tiber laminates					
	I - 40% Ti/58% Be		II - 55% Ti/36% Be		III - 63% Ti/31% Be	
	Roll direction	Transverse direction	Roll direction	Transverse direction	Roll direction	Transverse direction
Modulus, msi						
Measured	29.5	30.0	24.0	24.0	25.5	24.5
Predicted	30.6	30.8	23.7	24.0	22.9	23.2
Percent difference	3.7	2.7	-1.2	0	-10.2	-5.1
Poisson's ratio						
Measured	0.20	0.25	0.26	0.27	0.26	0.28
Predicted	.27	.27	.28	.29	.29	.29
Percent difference	35.0	8.0	7.7	7.4	11.5	3.6
Fracture stress, ksi						
Measured	93.8	67.6	104.9	103.5	114.1	103.9
Predicted (using eq. (3))	98.2	93.2	103.5	100.7	111.2	108.6
Percent difference	4.7	37.9	-1.4	-2.5	-2.5	-4.7
Density, lb/in.^{3}						
Measured	0.103	----	0.117	------	0.123	------
Predicted	.102	----	.116	------	.125	------
Percent difference	-.9	----	-.8	------	1.6	------

TABLE 7. - THIN-SPECIMEN IZOD IMPACT STRENGTHS[a]

Laminate type	Constituents	Test direction	IZOD impact strength, in.-lb/in.^{2}		Number of specimens
			Low	High	
I	Gr/Ep	Longitudinal	325	357	4
		Transverse	44	48	2
II	B/Al (diffusion bonded)	Longitudinal	277	286	2
		Transverse	229	247	2
III	B/Al (adhesive bonded)	Longitudinal	155	216	2
		Transverse	98	159	4
IV	Ti, B/Al	Longitudinal	247	253	2
		Transverse	179	224	4
V	Ti, B/Al, Gr/Ep	Longitudinal	634	720	2
		Transverse	186	202	2
Other Materials					
HTS/PMR-PI[b]		Longitudinal	204	206	2
HTS/PMR-PI[b]		Transverse	40	43	2
Glass-fabric/epoxy		------------	249	255	3
4-mil-diam. B/6064-Al		Longitudinal	253	272	2
Aluminum 0.6061		------------	756	914	2
Titanium (6Al-4V)		------------	2525	2558	2

[a]Specimen nominal dimensions: 0.50 in. wide by 0.06 in. thick.
[b]PMR = polymerization of monomeric reactants; PI = polymide.

TABLE 8. - SOME PROPERTIES OF TIBER HYBRIDS FOR POSSIBLE AEROSPACE STRUCTURAL APPLICATIONS

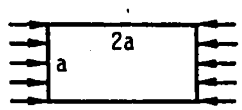
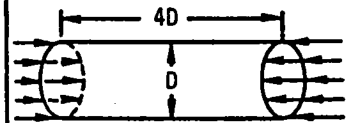
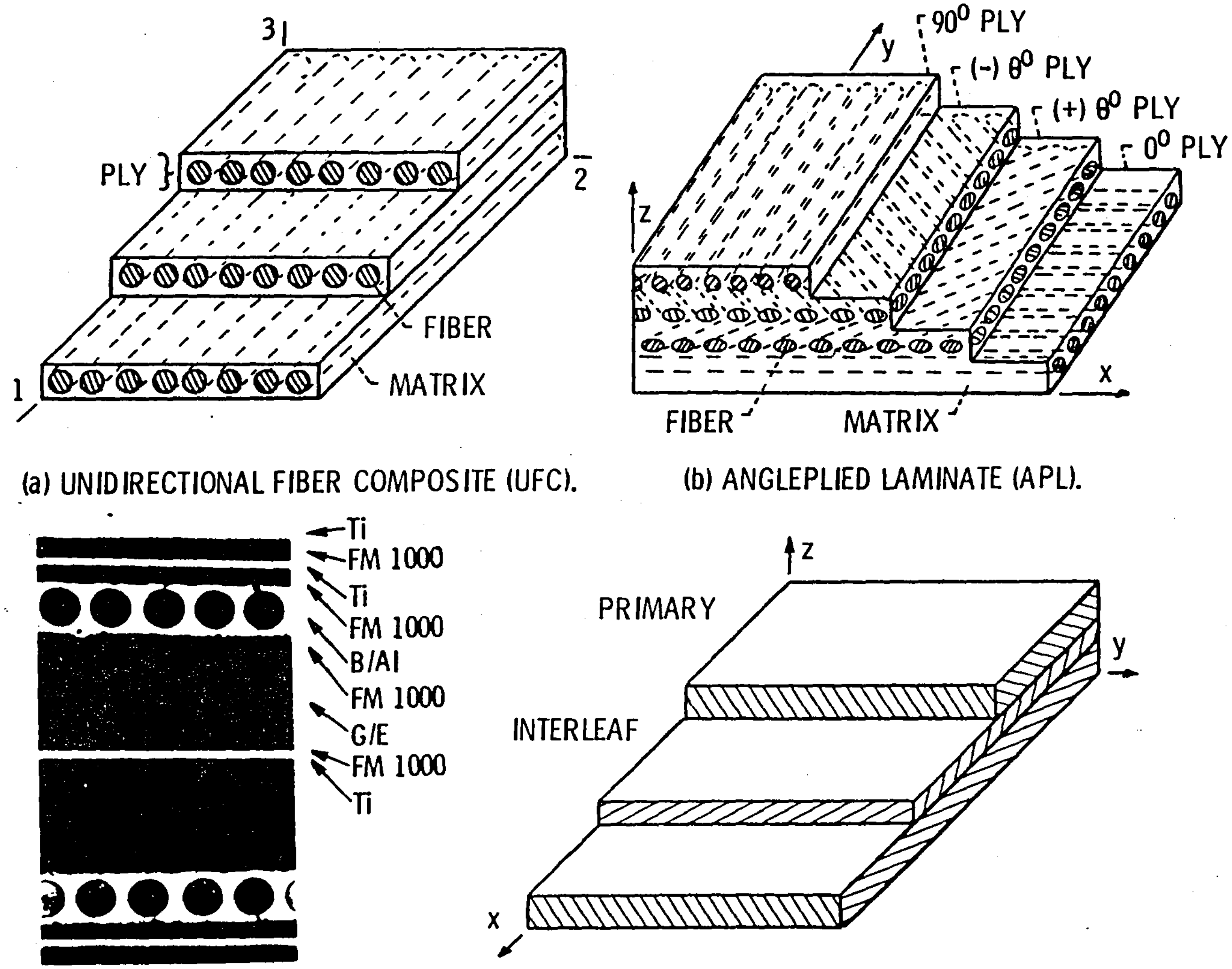
Material	Specific buckling stress, $\sigma_{CR}/t_c\rho$	
	Plate 	Cylindrical shell 
Tiber hybrids		
70% Ti/30% Be	402×10^3	4160
50% Ti/50% Be	532	6230
30% Ti/70% Be	818	9150
Other composites		
B/Al (0.50 FVR)	883×10^3	5120
B/E (0.50 FVR)	464	1310
T75/E (0.60 FVR)	~238	1180
AS/E (0.60 FVr)	~233	1150
Metals		
Steel	331×10^3	2442
Aluminum	307	2263
Titanium	307	2263

TABLE 9. - COMPARISON OF FREQUENCIES OF A HIGH-TIP-SPEED COMPOSITE BLADE USING VARIOUS CONSTITUENT MATERIALS

Mode	Frequencies for composite, Hz		
	HTS/K601 (±40°,±20°,0°)	HTS/PMR (±40°,±20°,0°)	30% Ti/70% Be[a]
1	361	400	662
2	939	960	1608
3	1178	1418	2108
4	1485	1658	2333
5	----	2427	3253
Nominal density, lb/in.^{3}	0.050	0.055	0.085

[a]Lamina thickness: 5 mil for titanium; 10 mil for beryllium.



(a) UNIDIRECTIONAL FIBER COMPOSITE (UFC).

(b) ANGLEPLIED LAMINATE (APL).

(c) SUPERHYBRID COMPOSITE (SHC).

(d) METAL/METAL LAMINATE (MML).

Figure 1. - General types of metal matrix laminates.

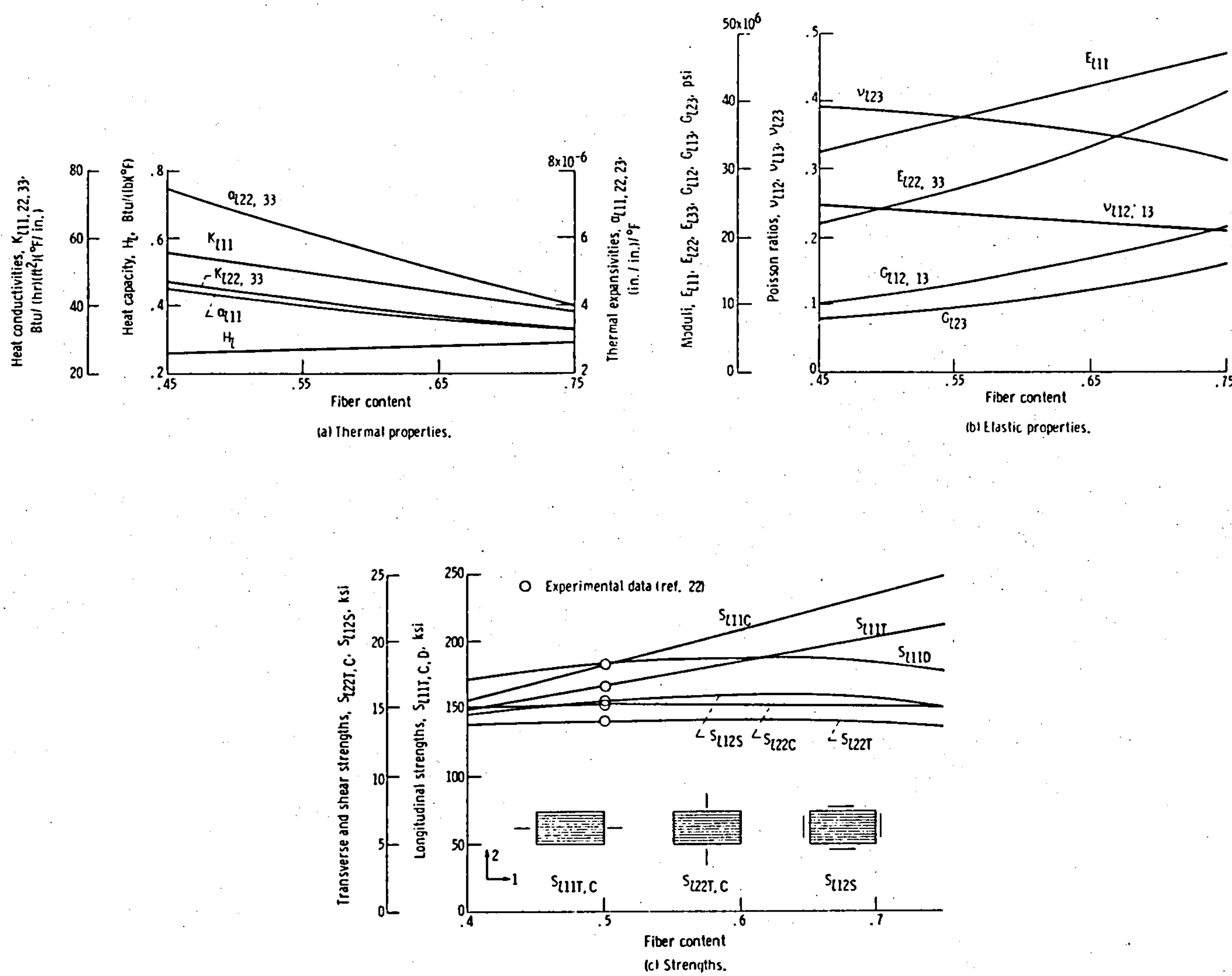
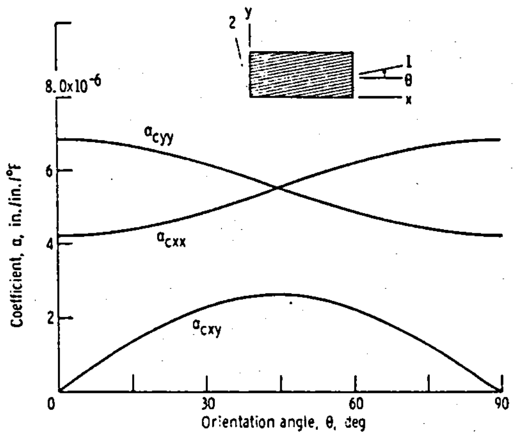
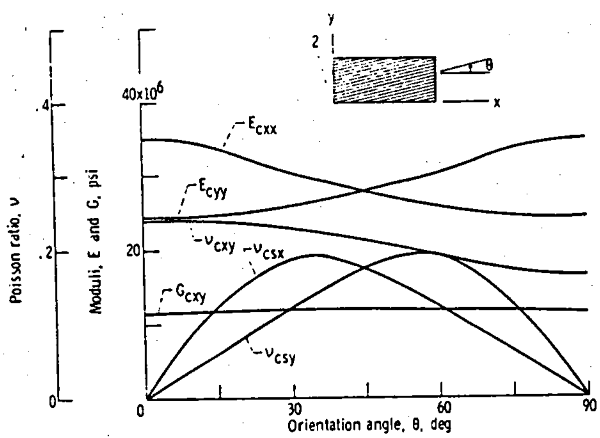


Figure 2. - Typical boron/aluminum unidirectional composite (ply) propertie, predicted using composite micromechanics (about 0.5 fiber volume ratio).

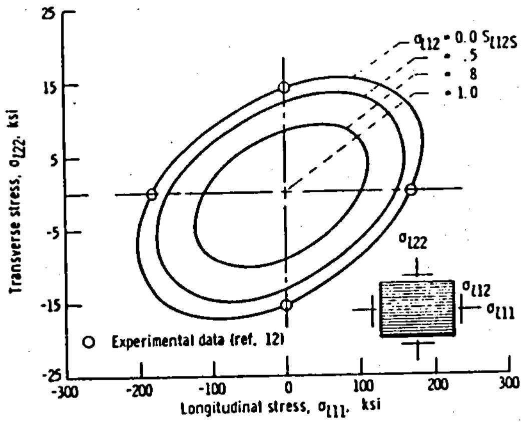


(a) Thermal coefficients of expansion for off-axis unidirectional boron/aluminum composites.

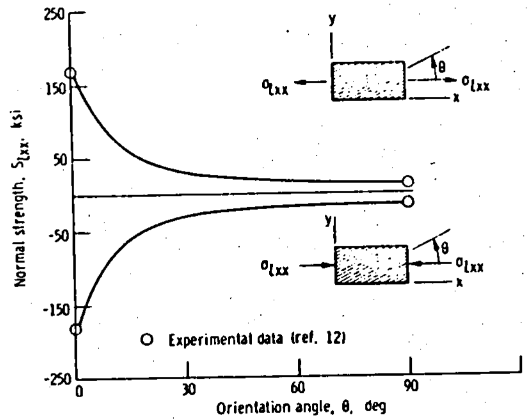


(b) Moduli and Poisson ratios for off-axis unidirectional boron/aluminum composites.

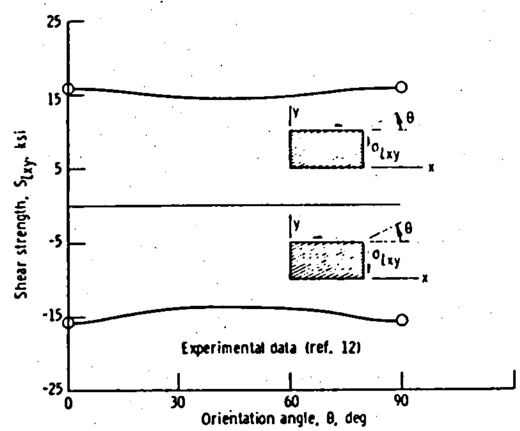
Figure 3. - Typical thermal and elastic properties of boron/aluminum metal matrix laminates predicted using composite macromechanics (about 0.5 fiber volume ratio).



(a) Failure envelopes under combined-stress for boron/aluminum.

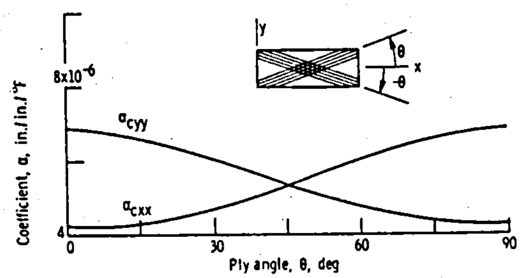


(b) Boron/aluminum off-axis normal load failure envelopes.

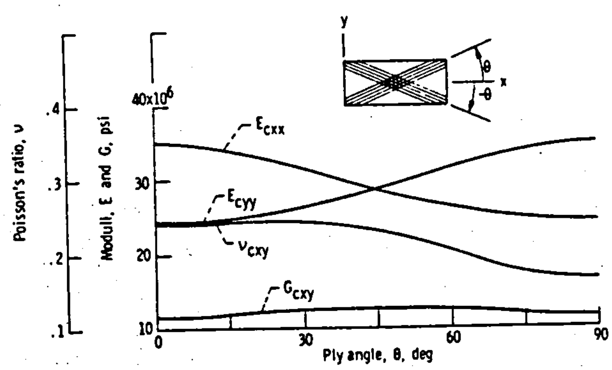


(c) Boron/aluminum off-axis shear load failure envelopes.

Figure 4. - Typical strengths of metal matrix laminates predicted using composite macromechanics (about 0.5 fiber volume ratio).



(a) Thermal coefficients of expansion for boron/aluminum angle-ply composites.



(b) Elastic constants for boron/aluminum angle-ply composites.

Figure 5. - Typical thermal and elastic properties of boron/aluminum metal matrix laminates predicted using laminate theory (about 0.5 fiber volume ratio).

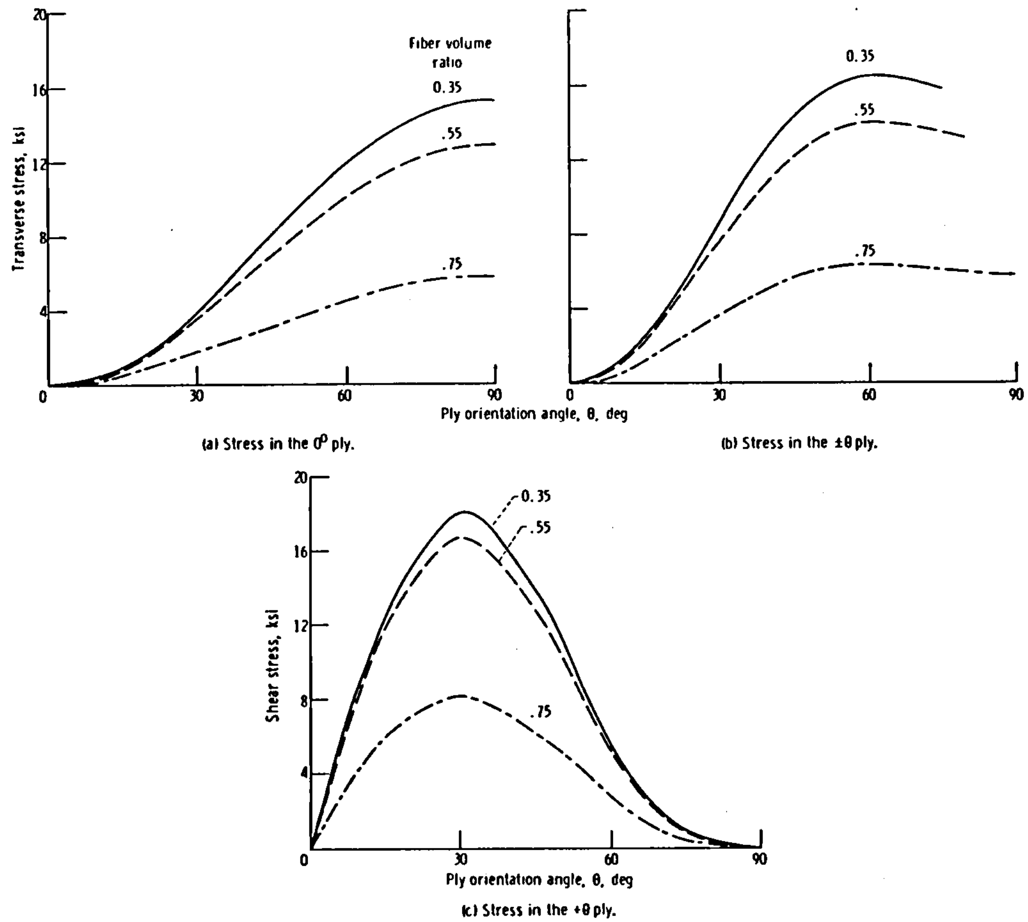
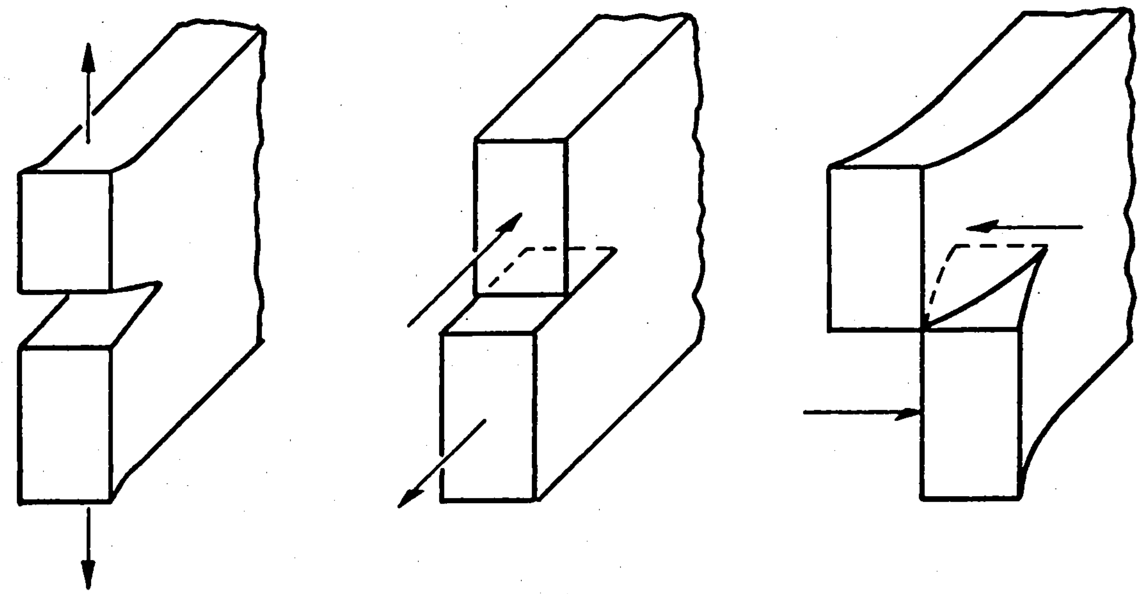


Figure 6. - Lamination residual stresses in boron/aluminum metal matrix laminates predicted using laminate theory (boron fiber/6061 - aluminum-matrix, 900° F temperature difference).



MODE I LOADING　　MODE II LOADING　　MODE III LOADING

Figure 7. - Primary load conditions and corresponding fracture modes used in fracture mechanics.

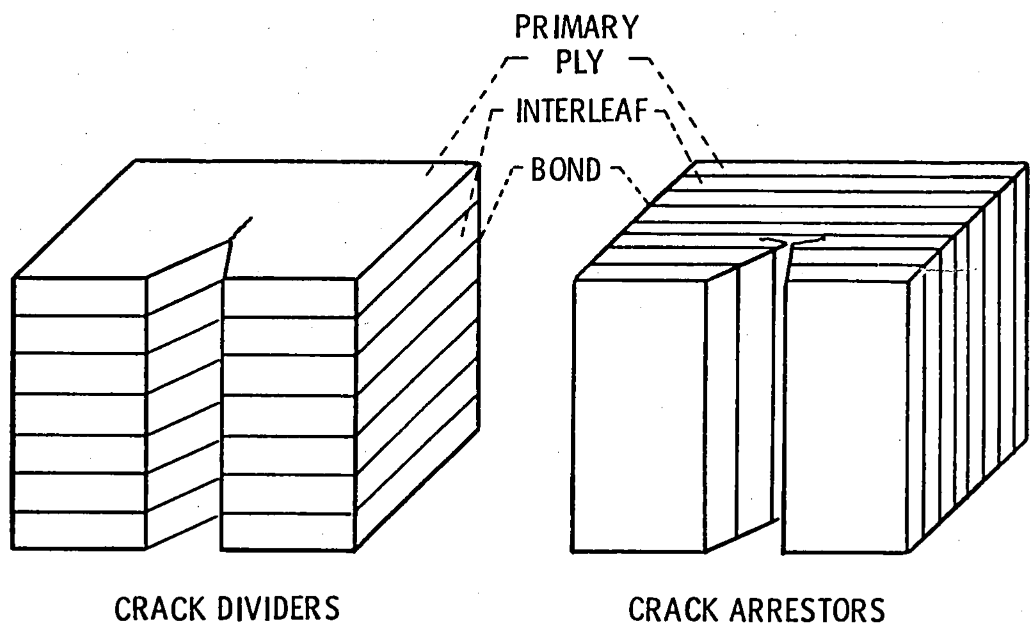


Figure 8. - Metal laminate concepts for fracture control.

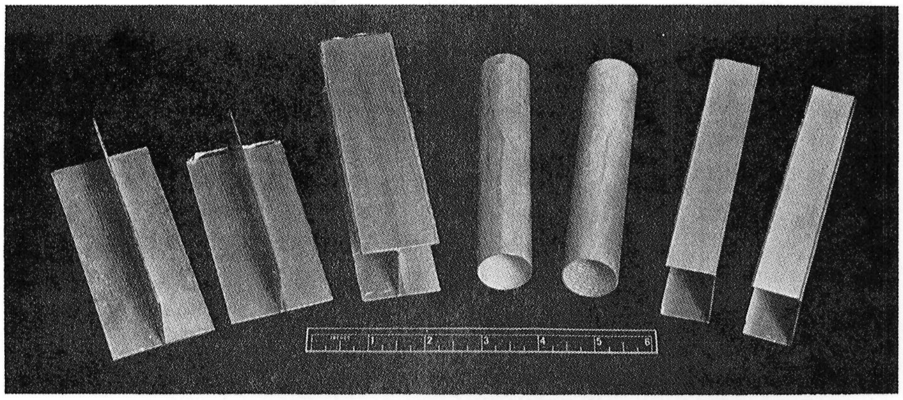


Figure 9. - Structural shapes for boron/aluminum metallic matrix laminates.

Figure 10. - Truss from boron/aluminum metallic matrix laminates.

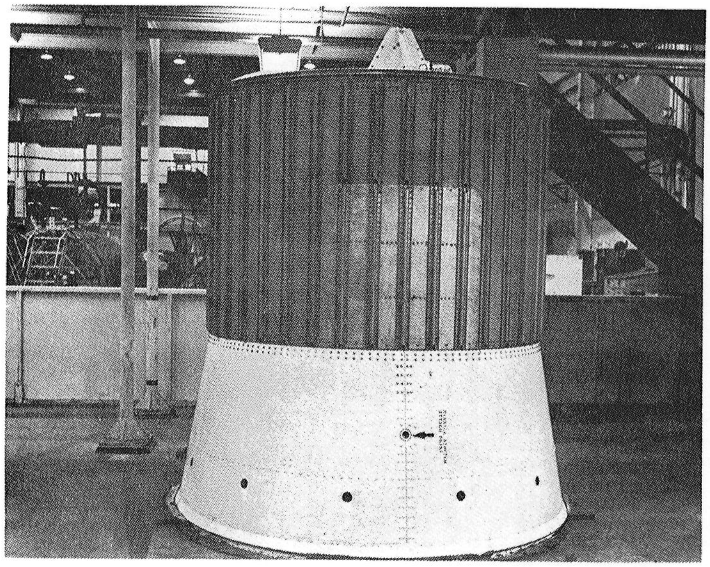


Figure 11. - Skin-stringer shell from boron/aluminum metallic matrix laminates.

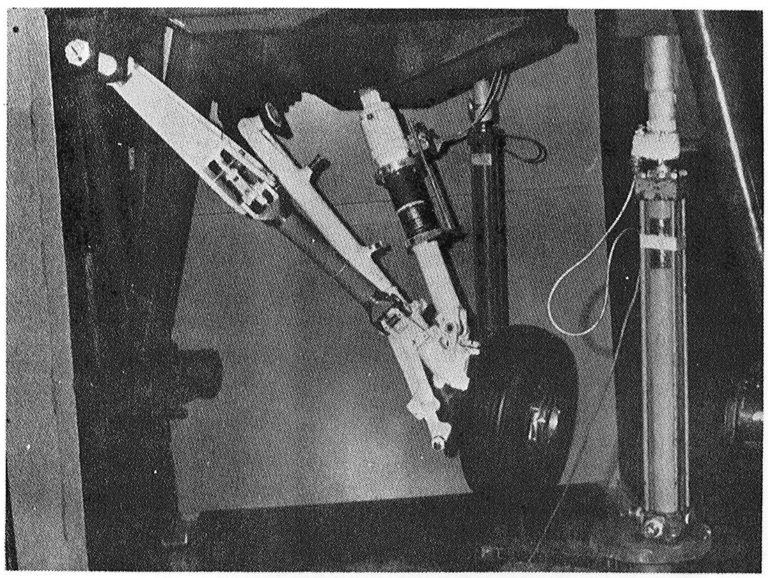


Figure 12. - Landing gear assembly from boron/aluminum metallic matrix laminates.

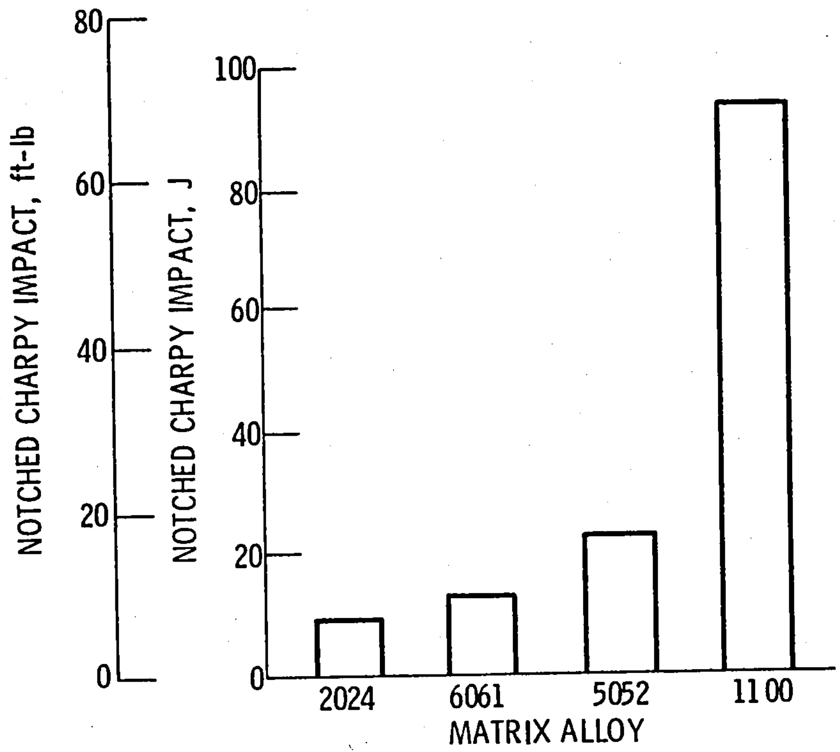


Figure 13. - Impact resistance of boron/aluminum unidirectional metallic matrix laminates (8 mil diam. fiber, 50 percent fiber, 0.5 fiber volume ratio).

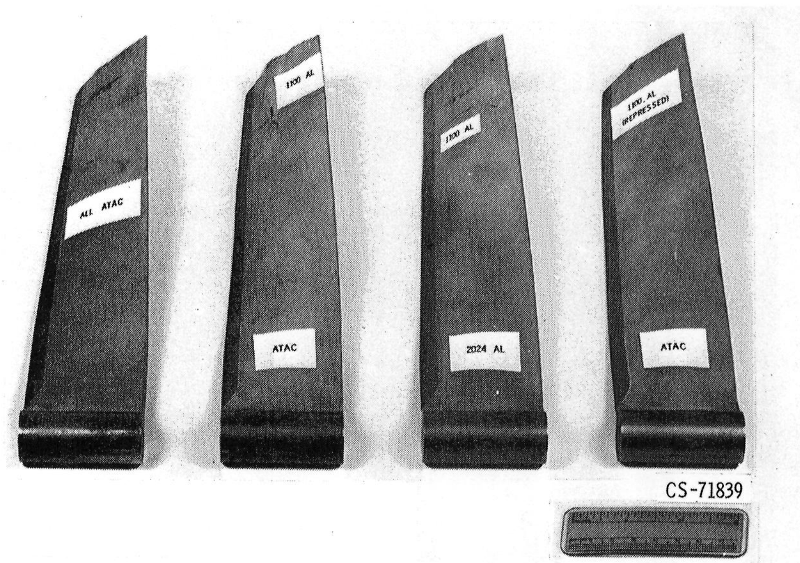
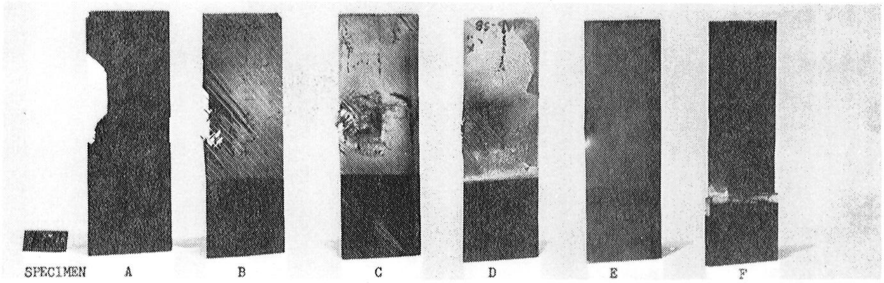


Figure 14. - Boron/aluminum metallic matrix fan blades after small (3 oz.) bird impact.



SPECIMEN	CONSTRUCTION	LEADING EDGE THICKNESS, in.	MIDCHORD THICKNESS, in.	PROJECTILE VELOCITY, ft/sec	PERCENT SLICE	KINETIC ENERGY/ THICKNESS, ft-lb/in.
A	Graphite-epoxy	0.029	0.150	828	55	814
B	Graphite-glass-epoxy	0.028	0.147	932	50	1048
C	Boron-glass-polysulfone-graphite-epoxy	0.029	0.161	935	40	801
D	Boron-glass-epoxy	0.030	0.163	884	40	694
E	Titanium-boron-Al-graphite-epoxy superhybrid	0.025	0.156	922	50	1192
F	Solid titanium (6Al-4V)	0.014	0.153	727	50	443

Note: Projectile was 1-in.-diam. gelatin sphere
Specimens A through E oriented at 30° incidence angle, specimen at 19° incidence angle

Figure 15. - Relative high-velocity impact assessment of superhybrids.

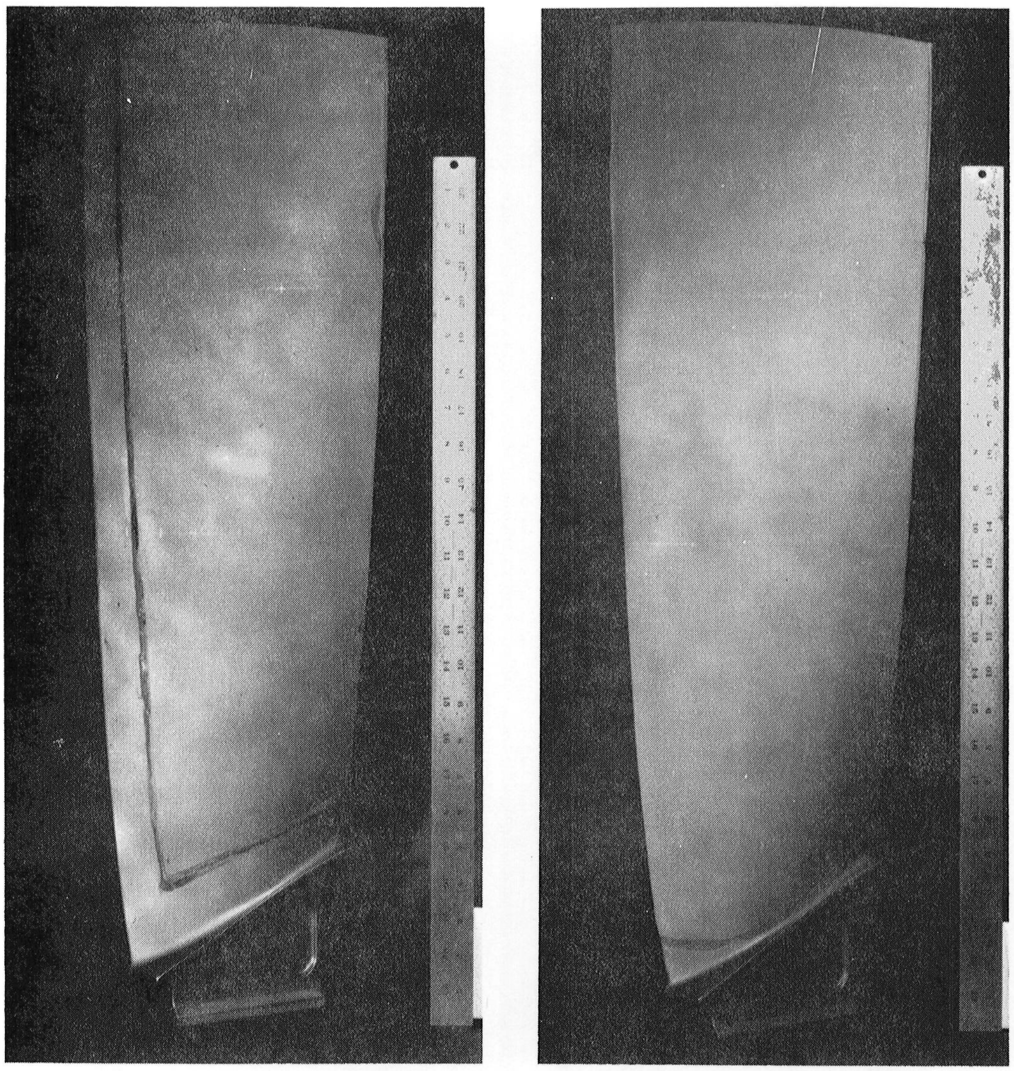


Figure 16. - Turbojet engine fan blades made with superhybrid-shell/titanium spar.

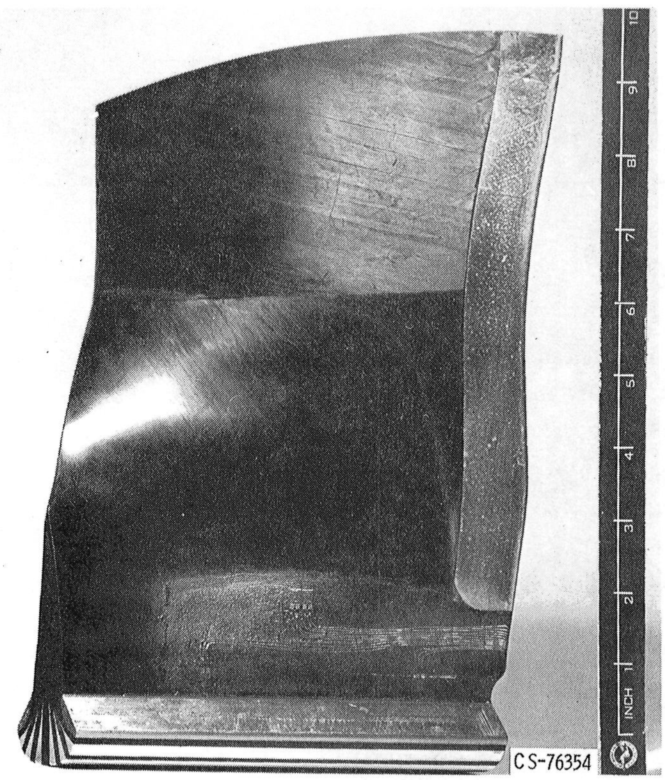


Figure 17. - High-tip-speed composite fan blade.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-81591		

4. Title and Subtitle	5. Report Date
LAMINATES AND REINFORCED METALS	October 1980
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
C. C. Chamis	E-570
	10. Work Unit No.
9. Performing Organization Name and Address	11. Contract or Grant No.
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
National Aeronautics and Space Administration Washington, D.C. 20546	Technical Memorandum
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A selective review is presented of the state-of-the-art of metallic laminates and fiber-reinforced metals called herein metallic matrix laminates (MMLs) for convenience. Design and analysis procedures that are used for, and typical structural components that have been made from MMLs are emphasized. Selected MMLs, constituent materials, typical material properties and fabrication procedures are briefly described, including hybrids and superhybrids. Advantages, disadvantages, and special considerations required during design, analysis and fabrication of MMLs are examined. Tabular and graphical data are included to illustrate key aspects of MMLs. Appropriate references are cited to make the article self-contained and to provide a selective bibliography of a rapidly expanding and very promising research and development field.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Metallic laminates; Fiber reinforced metals; Hybrids; Metallic matrix composites; Fibers; Metals; Fabrication procedures; Design; Analysis; Structural components	Unclassified - unlimited STAR Category 24

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		

* For sale by the National Technical Information Service, Springfield, Virginia 22161