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The status of nondestructive evaluation of metal matrix composites was studied. Tests that might be carried out were identified, and their potential advantages and limitations were assessed. Manufacturing processes were also reviewed, and a list of possible defects was developed. Recommendations are made for research needed in the development of new nondestructive testing techniques to detect and articulate flaws in metal matrix composites. In addition, studies of the interaction of material defects and failure modes

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NONDESTRUCTIVE EVALUATION OF METAL MATRIX COMPOSITES

Report of the
Committee on Nondestructive Evaluation of Metal Matrix Composites

NATIONAL MATERIALS ADVISORY BOARD
Commission on Engineering and Technical Systems
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ABSTRACT

The status of nondestructive evaluation of metal matrix composites was studied. Tests that might be carried out were identified, and their potential advantages and limitations were assessed. Manufacturing processes were also reviewed, and a list of possible defects was developed. Recommendations are made for research needed in the development of new nondestructive testing techniques to detect and articulate flaws in metal matrix composites. In addition, studies of the interaction of material defects and failure modes are recommended to develop a methodology for determining flaw criticality. Finally, the implications of quality assurance in structural design with metal matrix composites are discussed.

PREFACE

The development of metal matrix composite (MMC) materials has accelerated in recent years because of their unique combination of properties. Although contemporary technology in composite materials has focused on fiber-reinforced polymers, metal matrices offer acceptable performance at temperatures above the glass transition temperature of contemporary polymer-based composites.

Extensive efforts are currently under way to develop new MMC material forms and process technologies. Metallic materials containing continuous monofilament and continuous multifilament yarn as well as discontinuous reinforcements are being developed. This multiplicity of material forms and manufacturing processes has retarded the development of a fundamental understanding of the relationship between microstructure and material performance. Contemporary nondestructive test methods are of undetermined effectiveness in detecting all material defects because of the heterogeneous anisotropic nature of the MMC materials. Furthermore, the early stages of development of MMC process technology have produced materials containing a large number of different, but characteristic, defects. Unfortunately, the nature and importance of these defects (i.e., critical versus benign) is not clear. Therefore, the development of a fully effective nondestructive evaluation methodology can only be realized by the development of detection and flaw criticality assessment methods in parallel with the evolution of materials forms and manufacturing processes.

This report contains an assessment of the state of the art in nondestructive test methods, manufacturing technology, failure mechanisms, and design technologies for metal matrix composites. Conclusions and recommendations for the development necessary to achieve an effective nondestructive evaluation technology as determined by the committee are outlined. Technology reviews are supplemented by references from the literature.

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Chapter 1

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

This summary is a prioritized compilation of the committee's major recommendations. Additional, more specific recommendations are given in the respective chapters of the report dealing with particular facets of the nondestructive evaluation (NDE) of metal matrix composite (MMC) materials.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

1. Traditionally and characteristically, a material is developed, parts are fabricated and tested destructively, designs are finalized, and then nondestructive evaluation is considered. It is therefore recommended that the development of nondestructive testing (NDT) methods be integrated with the simultaneous development of manufacturing methods and flaw criticality assessment methods for MMC materials.

- The influence on performance of defect scale must be examined. Microscopic defects in the metallic phase should be examined to determine their influence on macroscopic composite properties.

- Continued emphasis should be placed on the study of fatigue damage mechanisms, focusing on the role that defect development plays in determining life.

- Modeling of properties of metal matrix composites is well developed for elastic behavior. However, modeling of plasticity and fracture are in an early stage of development. Efforts should be focused on modeling the numerous failure mechanisms in metal matrix composites, including the important effects of plasticity and residual stresses.

- Fiber-matrix interaction during primary and secondary fabrication can significantly affect constituent and resulting composite properties. Methods for determining and quantifying degradation of constituents need to be developed.

2. Understandably, first attempts at nondestructive testing of metal matrix composites have utilized procedures developed for metals and organic composites. However, because of different material characteristics and different anomolies, some customary procedures may be unworkable. It is therefore recommended that efforts be made to develop NDT methods tailored to the unique requirements of MMC materials. These methods should be grounded in a science base that yields quantitative physical measurements of defects in anisotropic, heterogeneous, and geometrically complex composite materials and structures. Automated means of data collection and interpretation are viewed as a necessity.

An investigation is proposed to evaluate the relative potential of the numerous NDT methods for specific MMC materials. Both near- and long-term solutions for the detection methods should be considered. A broad range of participants who reflect equivalent levels of expertise should be included in the investigation.

- Development of NDT methods that are appropriate for large-scale inspection of structural components and are economically feasible is recommended.

- It is recommended that NDE procedures, data, and models be disseminated to the "design community." Communication between the research and development and user and designer segments of the industry is required for the evolution of this technology.

- It is recommended that an interagency panel be established within the federal government to provide guidance and funding for research, innovation, data base development, and information dissemination on the nondestructive evaluation of metal matrix composites. This panel of distinguished scientists should include authorities in the areas of nondestructive test methods, design, failure mechanisms, and manufacturing science. The duration of the effort should not be less than 3 years.

3. The following defects and anomolies have been observed in MMC materials that will require detection by NDT techniques.

- Discontinuous reinforced materials

  agglomerations of reinforcement
  matrix-lean regions
  voids
  reinforcement particle size distribution
  inclusion of foreign matter
  reinforcement orientation
  alloy variation
  segregation of alloy constituent

- Continuous reinforcement--monofilament

  disbonds between preforms
  filament splices
  filament spacing distribution
  filament degradation due to matrix/fiber reactions
  filament "birth defect"
  foreign inclusions
  voids

- Continuous reinforcement--multifilament yarn

  incomplete preform infiltration
  irregular preform shapes
  porosity
  matrix cracking
  fiber misalignment
  delamination of encapsulated foil
  disbonds and matrix cracks
  fiber degradation due to secondary forming
  fiber degradation due to matrix/fiber reactions
  fiber spacing distribution

DETAILED RECOMMENDATIONS

1. Generic Reseach

- Undertake a study to establish the relative sensitivity of multiple NDT methods such as X-ray, acoustic emission, thermographic, holographic, ultrasonic, and electrical in detection of given flaw geometries in given metal matrix composites.

- Develop NDT methods and/or empirical models to determine the nature and extent of fiber property degradation in situ due to thermal, mechanical, and metallurgical processing.

- Develop a technique, such as microhardness, to determine in situ yield strength of the metallic matrix phase.

2. Ultrasonic Methods Development

- Ultrasonic phase fronts become distorted as the waves propagate through the inherently inhomogeneous structure of metal matrix composites. To avoid serious errors arising from phase cancellation effects at piezoelectric receivers, phase-insensitive ultrasonic detection techniques should be improved and evaluated in the study of metal matrix composites.

- To generate and acquire the maximum possible information, wider bandwidth and thus higher frequency ultrasonic transducers exhibiting adequate sensitivity should be developed for MMC applications.

- Imaging based on quantitative estimates of ultrasonic attenuation and backscatter measured over a broad bandwidth using a phase-insensitive receiver appears to hold promise. Results of these ultrasonic evaluations should be correlated with the results of direct determination of mechanical properties in the same locations as an approach to developing models for relating ultrasonic measurements to material performance.

- Nonlinear ultrasonic effects appear to provide a sensitive probe for investigating variations in material properties. Approaches to the nondestructive evaluation of metal matrix composites based on nonlinear effects, including harmonic generation and higher order elastic constants, should be evaluated.

- Methods for scanning relatively large areas and volumes are essential if ultrasonic techniques are to be practical. Both mechanical and phased-array electronic scanning techniques appropriate to the investigation of parts exhibiting various geometries should be developed. Ultrasonic holography and photoacoustic spectroscopy should also be evaluated as potential imaging modalities. Computer-controlled data acquisition must be incorporated early in the design of scanning systems.

- Broad-bandwidth ultrasonic signals contain substantial information that can usually be analyzed most effectively by Fourier transform and related analytical techniques. Investigators of ultrasonic nondestructive evaluation should be provided with fast waveform recorders to capture the data reliably and computers of substantial speed and capacity equipped with array processors to carry out transformations rapidly.

- Relating the results of ultrasonic interrogation to materials performance is inherently a problem of inference in which insufficient data are available to completely specify the solution. Thus, the goal must be to achieve a "best estimate" of the local characteristics of a metal matrix composite from the limited information generated. It is recommended that maximum entropy or similar Bayesian approaches to the problem of inference be assessed as an approach toward introducing the least amount of bias into the prediction. Such an approach may lead to fewer parts being rejected as a result of unsatisfactory evaluation.

- Adequate nondestructive evaluation of large complex structures may require a combination of techniques including, for example, the use of ionizing radiation, dye penetrant, and ultrasound. A unified program designed to integrate several NDE modalities to permit practical nondestructive evaluation of actual structures (as opposed to laboratory specimens) should be initiated in parallel with laboratory investigations. The results of this program should serve to guide technique development efforts by delineating the scale and speed required for practical use of each modality.

3. Flaw Definition Modeling in Continuous Reinforced Materials

   - Conduct a detailed assessment of existing models for prediction of strength of continuous fiber metal matrix composites and correlate with existing materials data.

   - Develop models for the prediction of property degradation as a function of defect geometry for dominant failure modes. Modes to be considered should include axial and transverse tensile strength, axial compressive strength, and shear strength.

   - Determine the relationship between axial and transverse fatigue behavior given metal matrix systems and in situ matrix yield strength, toughness, and bond strength. Develop analytical and/or empirical models of these phenomena.

4. Flaw Definition Modeling in Discontinuous Reinforcement

   - Undertake a study to define the predominant failure modes and processes for metal matrix composites with discontinuous reinforcement.

   - Develop models to predict the property degradation as a function of defect type and geometry (including fiber degradation) for primary failure modes.

   - Determine the relationship between fatigue behavior of discontinuous MMC systems and in situ matrix differences. These variables would include reinforcement geometry, such as orientation distribution, size distribution, and variation in local volume fraction.

   - Develop analytical and/or empirical models of these phenomena.

Chapter 2

NONDESTRUCTIVE TEST METHODS

In the following sections the technical bases for nondestructive evaluation methods are addressed. Each section contains the following elements: (1) a brief description of the physical principles underlying the method, (2) a discussion of prior art with respect to metal matrix or similar composite systems, (3) assessment of the applicability of the method to metal matrix composites, and (4) evaluation of the future potential of the method. The presentation is organized according to physical principles underlying the NDE techniques, as indicated in Table 1.

A thorough literature search was conducted in preparing this review. Because of the limited amount of information on the nondestructive evaluation of metal matrix composites generated by this literature search, the content of the state-of-the-art reviews draws also on the experience and knowledge of committee members from universities, industry, and government. Furthermore, references to work on composite systems consisting of nonmetal matrix materials have been included where applicable. The methods discussed in this section cover the full range of NDE technology, from current production and field use to advanced laboratory research methods.

The selection of optimum NDE methods to assure quality cannot be made on the basis of material type alone. In addition, the following factors must be considered: geometry, service environment, defect type and location, and potential failure mode. Furthermore, the time and cost required for the NDE inspection must be included in the determination of the methods of choice. It is frequently necessary to evaluate the trade-offs between the information obtained with a particular inspection technique and the associated time and cost. One technique may offer better sensitivity and resolution, whereas another may offer greater speed but poorer resolution. Large-scale inspections are often required to identify regions requiring detailed inspection. Therefore, complementary methods are often necessary to ensure reliability.

PENETRATING RADIATION

X-Radiography

X-radiography is performed by illuminating one side of the test object with X-rays and recording the transmitted intensity on the opposite side.

TABLE 1 MMC NDE Method Categories

Penetrating Radiation
- X-ray
- neutron
- diffraction

Penetrant

Optical
- holography
- visual

Thermographic
- infrared thermography imaging
- photo acoustic spectroscopy

Acoustic Emission

Electrical and Magnetic
- eddy current
- electrical potential
- magnetic

Acoustic-Mechanical
- tap test
- low-frequency resonance

Ultrasonic
- contact
- C-scan
- velocity
- attenuation
- nonlinear effects
- imaging

Radiography operates on the principle that a defect or flaw in the test object will cause a change in the transmitted X-ray intensity. The most commonly used hardware for radiography includes an X-ray machine with variable energy settings as a source of X-rays and film as a means of recording the X-ray intensity transmitted through the test object.

The amount of radiation passing through the test object is primarily a function of the object's density, thickness, and atomic number, as well as the energy of the illuminating X-rays. Typically, as X-ray energy is lowered, the transmitted intensity becomes more sensitive to flaws in the material. If, however, the X-ray energy is too low, the film will remain unexposed. Thus, selection of the proper X-ray energy is critical to providing the optimum contrast between defective regions and the surrounding acceptable regions of the material.

X-ray exposure techniques for metal matrix composites do not differ from those for other materials. The major difference between radiography of metal matrix composites and homogeneous metals lies in the types of defects that are detected. Radiography provides planar spatial detail far in excess of either eddy current or ultrasonic tests. A major limitation of conventional film radiography is that it is insensitive to defects perpendicular to the film plane.

Radiography can be extremely useful for investigating fiber orientation in continuous fiber-reinforced composites (Navy, Department of 1981). Such orientation is particularly critical in unidirectional composites with poor off-axis properties. Other fiber-related defects, such as broken or missing fibers, can also be detected in most composite systems. The limiting factor for the detection of fiber-related defects is related to the number of layers of fiber rows or monofilament in the specimen. The superimposed images of multiple plys tend to mask the image of any single ply.

The detection of cracks in continuous fiber-reinforced metal matrix composites by means of radiography is not as reliable as it is with homogeneous metals. The unidirectional nature of most continuous fiber composites causes cracks to align themselves in the fiber direction. Such alignment can easily prevent detection by making it difficult to distinguish fiber images from crack images on a radiograph.

Radiography has also proved to be a useful tool in the detection of noninfiltration of graphite fiber-metal composite precursor materials. Radiographs of graphite-aluminum precursor wires easily reveal a 0.005-in. noninfiltration in a 0.025-in.-diameter wire. Attempts to automate such an inspection by filmless radiographic gauging techniques are currently under way at Aerospace Corporation and at the Naval Surface Weapons Center (Navy, Department of 1980a).

Radiographic exposure techniques for discontinuous whisker- or particulate-reinforced aluminum are identical to those for aluminum alloys. Silicon carbide and aluminum have almost identical X-ray cross sections at the energies used for radiography. The two defects most commonly detected by radiography in discontinuous SiC-Al are cracking and porosity. The detection of cracks is no different than it is in homogeneous metals, but the radiographic detection of porosity is often more complicated. The porosity resulting from the SiC-Al powder metallurgy fabrication process is extremely fine. Individual pores are usually too small to be seen as discrete images on a radiograph. Instead, the cumulative effect of superimposed pores must be present to cause a noticeable change in film density. Specimens that have varying degrees of porosity from point to point may show slight and very gradual changes in radiographic density, but specimens with uniform microporosity will yield a uniform radiography and may be easily mistaken as good. Ultrasonic testing has demonstrated greater promise for detecting such microporosity (Navy, Department of 1982).

The detection of weld flaws is ideally suited to radiography. This is particularly true with SiC-Al weldments, where macroporosity is a predominant flaw. Other typical flaws that are readily detected by radiography include lack of fusion, inclusions, undercut, and other defects typical to welding of homogeneous metals as well.

Neutron Radiography

The principles of neutron radiography are similar to those of X-radiography. Both techniques utilize a source of radiation together with a medium such as film to record the intensities transmitted through the test object. The most efficient sources of neutrons are nuclear reactors (Barton 1976). Here, fast neutrons are moderated to produce thermal neutrons prior to passing through the test object. In order to convert neutrons into an image on a photographic film, it is necessary to place a thin foil of gadolinium adjacent to the film. A major limitation of neutron radiography is the absence of efficient portable sources, thus requiring that articles be transported to a reactor facility for testing. Exposure time is based on a trade-off between resolution and throughput (Cutforth 1976).

The major advantage of neutron radiography is that it often magnifies the radiographic contrast between elements, as compared to X-radiography. For example, the mass absorption coefficient differences between carbon and aluminum are far greater with neutrons than with X-radiation. Thus, the internal structure of composite materials is often enhanced on a neutron radiograph.

In spite of some of the practical limitations of neutron radiography, it has proved useful as a research tool in understanding the nature of defects in metal matrix composites. This is particularly the case in graphite-reinforced aluminum, where neutron radiography has been demonstrated for the detection of noninfiltrated precursor wires in multiple-ply panels (Anderson and Blessing 1979; Navy, Department of 1980a). The ability of neutron radiography to enhance the radiographic contrast between elements such as boron, oxygen, carbon, silicon, and metallic matrices will no doubt continue to prove useful in understanding the nature of certain fabrication defects in metal matrix composites.

Unless significant advances occur in the production of neutrons from portable or semiportable devices, it is not likely that neutron radiography will play a significant role in the production or field inspection of metal matrix composites. Instead, neutron radiography will most likely be limited to its current role as a research tool.

X-ray Diffraction

X-ray diffraction as a means of evaluating residual stresses has developed over the last 50 years to a point where it is often the standard against which other stress measurement techniques are compared. The technique utilizes the principle that the interplanar spacing of material grains is a function of stress and this spacing can be determined by studying the angles with which X-rays diffract from the specimen surface. By measuring the angular diffraction peaks at two different incident angles, one is able to calculate residual stress. The technique is generally limited to surface stresses; however, in certain cases, subsurface stress information can be obtained through more sophisticated modifications of the technique (Cohen 1980).

The application of residual stress measurements to metal matrix composites can often be a powerful tool in understanding their mechanical behavior. Most composites are combinations of materials with vastly different properties. The combinations of constituents is a deliberate attempt to capitalize on the combined effect of dissimilar materials acting in unison. Differences in elastic properties and coefficients of thermal expansion cannot help but lead to unusual stress distributions and large residual stresses.

Residual stresses in graphite-reinforced aluminum have been measured utilizing X-ray diffraction methods. The results indicate large residual stresses in the fiber direction as well as surprisingly large stresses in the transverse direction. Stresses in the fiber direction were entirely expected because of the tremendous difference in thermal expansion coefficients of graphite and aluminum along the fiber direction. Stresses in the transverse direction were too high to be attributable to thermal expansion coefficient differences and were thus probably the result of matrix yielding in the fiber direction (Tsai et al. 1981).

DYE PENETRANT TESTING

Penetrant testing is a means of aiding visual inspection for surface defects such as cracks. The process operates on the principle that penetrant dyes are absorbed into surface-breaking defects and can thus be utilized to make the defects more visible. The first step of the penetrant inspection procedure is a careful cleaning of the test object to remove all surface oils and contamination. Next, the dye is applied to the surface and allowed to soak into whatever defects may be present. The dye is then removed from the surface, leaving only the dye that has become trapped in surface cracks. Finally, a powder-like developer is applied to the test object. The developer draws residual dye out of cracks, making their presence highly visible. The visibility of dyes is often further enhanced via ultraviolet fluorescence.

The applicability of dye-penetrant testing to metal matrix composites is essentially the same as with more conventional materials. Penetrant testing acts only as a visual aid in detecting surface defects. A major advantage of penetrant testing is its low cost. Specialized inspection hardware or training is usually not required. In addition, penetrant testing is generally not affected by the unique specimen geometries that can often complicate or eliminate other NDT methods. For these reasons, penetrant testing is widely used as one of several means of testing metal matrix composites.

For continuous fiber-reinforced metal matrix composites, penetrant testing has been demonstrated by both material producers and users as a convenient means of detecting surface cracks. In the case of graphite-aluminum composites, penetrants are also a useful means of detecting breaks in the surface cladding of the composite (Anderson and Blessing 1979). Such breaks are significant in that they can easily lead to accelerated corrosion.

Discontinuous whisker- and particulate-reinforced metal matrix composites have also benefited from penetrant testing. Here, the application has been toward the detection of cracks and surface porosity.

It is likely that penetrant testing of metal matrix composites will increase as these materials come into use. The utilization of metal matrix composites will lead to structures with geometries considerably more complicated than the simple generic shapes produced for research and development purposes. It will also become increasingly likely that field inspection of MMC components without disassembly will be required. These limitations, together with inspection cost and time constraints, may place a heavier dependence on penetrant testing in the future than is now the case. Fortunately, the technology is well established (Betz 1969).

OPTICAL METHODS

Holography

Holographic nondestructive testing (HNDT) detects very small (in the order of the wavelength of light) changes in surface displacement as the result of external stimulus (Erf 1972). Abnormalities such as unbonds and changes in material properties will cause variations in surface displacement that are detectable as changes in the interferometric fringe patterns. Comparison of the fringe patterns observed under the same loading conditions on a defect-free part with those from a part with known defects is the basis of determining defect sensitivity and resolution.

There are several means of applying stimulus to a part during HNDT, include acoustic, thermal, and mechanical methods. Vibrational shakers and/or piezoelectric transducers are used to set up standing-wave vibrations in a part. Various structural and defect resonances are created by varying the excitation frequency. Proper fixturing and selection of the amplitude and frequency of excitation are critical for a successful HNDT method. Differential thermal heating is another method of inducing differential surface displacement. Thermally induced strain involves expansion and contraction of the part caused by nonuniformity of thermal conductivity properties. Mechanical methods can be quite simple, as in subjecting the part to a proof load for example, hydrostatically in a pressure vessel, or more complicated, as in multipoint loading of a total structure. In all cases, the success of HNDT inspection is highly dependent on the design and application of the external stimulus.

HNDT methods as applied to metal matrix composites are primarily sensitive to surface or slightly below-surface defects such as disbonds, delaminations, and near-surface inclusions. As the depth of a defect below the surface increases, the resolution sensitivity will decrease. HNDT methods have been used with considerable success on composite rocket motor cases, composite skin structures, honeycomb structures, and MMC fan blades (Erf 1974). The technique has the advantage of permitting inspection of large areas rapidly and is generally unaffected by material variations that do not locally affect part compliance. HNDT is, however, part-specific in that often a new technique is required for each structure/defect type combination. Tests have been performed in production environments, but generally the part must be vibrationally isolated from the environment. Although the energy level of the lasers commonally used for HNDT do not pose any serious health problems, safety regulations often impose working restrictions that are cumbersome.

Visual

Visual inspection is no doubt the oldest and most commonly employed NDT technique. Many serious defects have been discovered by simple visual surface inspection. A significant commercial technology base exists for applying this technique to specific geometries.

THERMOGRAPHIC METHODS

Infrared Thermography

Thermographic nondestructive testing measures the absolute value and spatial variation of the surface temperature of a part. Modern instrumentation is capable of recording spatially and temporally resolved temperature distributions accurately over a wide temperature range. Temperature resolution in the order of 0.1°C and spatial resolution of 0.1 mm is well within the state of the art (Reifsnider et al. 1980; Henneke and Jones 1979). As in holography, an external stimulus is required to induce a thermal gradient within the part. This gradient may be introduced mechanically, thermally, or acoustically.

A mechanically induced thermal gradient is created during mechanical loading of a composite coupon. Heat is generated via two mechanisms: first, as the result of the release (and subsequent conversion to heat) of strain energy and, second, by internal friction caused by the rubbing together of fracture surfaces. Thermography has been used successfully to detect the formation and subsequent propagation of defects in boron-epoxy and boron-aluminum fiber-reinforced composites (Reifsnider and Williams 1974). Because metal matrix composites have a higher thermal conductivity than polymer matrix composites, the thermal gradients generated under the same loading and part geometry conditions are significantly lower.

A thermally induced thermal gradient is achieved by heating the part nonuniformly, usually by using a heat lamp or resistive heat source. This technique has been used to detect major disbonds, voids, or delaminations in polymer matrix composites. Because of the high thermal conductivity of metal matrix composites, the sensitivity of the technique is anticipated to be low for this application. Further, since this type of stimulus results in a quasi-steady-state thermal condition, the sensitivity is nominally less than for other methods of stimulus.

Acoustically or vibrationally induced thermal gradients are the basis of an inspection method called vibrothermography. This technique induces thermal gradients acoustically (or vibrationally) much the same as surface displacement gradients are induced in HNDT. The technique is sensitive to any defect, surface or subsurface, that can be induced to produce frictional heat. As in the case of HNDT, sensitivity and reproducibility are highly dependent on the means of application of vibrational energy and the frequency of excitation. These test conditions are usually specific for a given part configuration and defect, and therefore the test technique often must be tailored to each application. The best results are usually obtained during transient vibrational loading rather than during steady-state loading. During transient vibrational loading, the heat pattern from the defect will "bloom" and then fade as the heat dissipates within the structure. The lower the thermal conductivity of the part, the greater the temperature rise during the bloom and the slower the fading during dissipation. Hence, although the method has been applied successfully to metal matrix composites, best results have been obtained for polymer matrix composites.

In summary, thermal methods are sensitive to surface and subsurface defects; the sensitivity decreases with increasing depth below the surface. They are useful for inspecting large surface areas rapidly but must be specifically tailored to each application. They are best suited for materials with a low thermal conductivity, and thus marginally appropriate for application to metal matrix composites.

Photoacoustic Spectroscopy

Photoacoustic spectroscopy is a technique wherein a chopped, focused light beam striking an absorbing surface is converted to heat, which, via thermal expansion, is subsequently converted into sound at the chopping frequency. The sound is amplified and detected by a microphone in the surrounding area or by a transducer attached to the material. The method has the unique ability to investigate subsurface features without regard to surface irregularities, as well as surface features alone. The surface chopped light generates a "thermal wave" that propagates into the material at a slow rate compared to the sound velocity. Consequently, by phase detection, one can literally "pick off" the portion of a signal coming from a given depth in the material.

Photoacoustics has evolved rapidly since 1973 (Rosencwaig 1973, Rosencwaig 1977, Rosencwaig and Gersho 1976, Rosencwaig 1975, Royce et al. 1980, Dewey 1974) and since 1980 (Brandis 1980, Jackson and Amer 1980, Opsal and Rosencwaig 1982, Busse and Ograbeck 1980, Busse 1981, Ringermacher and Heyman 1981) has been demonstrating unique NDE capabilities. The technique is fundamentally sensitive to changes in material thermal properties arising from the presence of voids, inclusions, defects, and impurity concentrations at micron resolution levels. Consequently, it shows promise and, indeed, is even now being applied to characterize defects in ceramics and integrated circuits. Applications are also moving in the direction of flaw inspection of advanced ceramic turbine blades and composite materials.

The continued development of photoacoustics and transducer detection methods will bring laboratory photoacoustics into an industrial NDE environment. Metal matrix composites are ideal candidate materials for the application of this relatively new technique because of the high thermal conductivity of the matrix. To date, however, little work has been initiated in this area. There is the potential for measurement of localized coefficient of thermal expansion, voids, discontinuities, and inclusions. However, developmental efforts are required to move the technique from the laboratory to an inspection environment.

ACOUSTIC EMISSION

When a part is subjected to external loading high enough to cause incremental localized damage propagation, there will be strain energy released that will generate a stress wave. This stress wave will propagate to a surface of the part, where it is detected by a piezoelectric sensor and converted into an electrical signal. The detection, location, and subsequent processing of this signal is termed acoustic emission (AE) technology. There are two main technical hurdles to be overcome for a successful application of AE methods to a structure or process. First, the AE events of interest must be detected and discriminated from extraneous noise sources. Second, signal processing techniques must be devised that are capable of quantitatively categorizing and rating the severity of detected defects. AE technology, in its present state of development, is often capable of differentiating between real and extraneous sources and determining the location of an AE source. However, the present state-of-the-art instrumentation is not capable of quantitatively categorizing and rating the severity of an AE source. This is true for all material applications, not only composites.

Composites, however, are ideally suited for inspection by AE methods. Their heterogeneous nature gives rise to many AE sources of considerably high energies. As a result, there have been numerous applications (Bailey and Pless 1981, Sheriff 1981, and Shuford et al. 1981) where successful qualitative inspections have been developed. AE methods have been used by Dunegan/Endevco Corporation to inspect fiberglass "cherry-picker" structures. Numerous petrochemical companies have used AE to inspect composite pressure vessels--to such an extent that a special subcommittee within ASME has been formed to develop test specifications. Considerably more AE work has been applied to polymer matrix composites than to metal matrix composites, primarily because of the more widespread use of polymer (particularly fiberglass) matrix composites. AE has been used to monitor fatigue damage propagation in boron-aluminum fiber-reinforced composites (Williams and Reifsnider 1974). The results of this work have shown a linear relationship between total cumulative AE activity and change in dynamic compliance.

Recent research has sought to develop instrumentation and signal processing methods capable of quantitatively assessing type and severity of an AE event. The development of nonresonant sensors, highly broadband electronics, and new signal processing methods promise the availability of significantly more quantitative AE test methods and instrumentation in the near future (Ringermacher and Williams 1982). As this technology becomes available, AE methods will be feasible for global examination of a structure during the application of a proof-load. However, the technique will always be limited by the ability to realistically proof load the structure. Further, the more complicated the structure, the more difficult it is to locate and quantitatively characterize AE sources.

ELECTRIC AND MAGNETIC METHODS

Eddy-Current Testing

Eddy-current testing of metals is achieved by inducing localized circular electrical currents in the test object. The flow of these currents can indicate the presence of discontinuities. Currents are typically induced by placing a small coil driven with an AC signal adjacent to the test object. The alternating magnetic field of the coil generates alternating eddy currents in the object. These eddy currents in turn generate their own magnetic field, which affects the phase and amplitude of the AC signal in the test coil. Thus, by carefully monitoring the phase and amplitude of the currents in the test coil or probe, one can either detect discontinuities or monitor the electrical conductivity of an object. A basic limitation of eddy-current testing is that eddy currents fall off in magnitude at an exponential rate from the surface at which they are generated. Thus, eddy-current testing is typically only useful for testing material at or near the inspection surface. Specific inspection depths depend on specimen conductivity, permeability, and test frequency, but in almost all cases the depths are less than 0.10 in.

Eddy-current testing has been demonstrated on both continuously and discontinuously reinforced metal matrix composites. Although eddy-current testing is applicable to both types of composites, the particular technique and rationales are quite different for each material.

The presence of axial cracks in unidirectional composites may be acceptable for certain applications. Such cracks encounter little resistance as they grow to ultimate failure. The detection of such defects by radiography and ultrasonics is often frustrated by the indications of fibers or fiber bundles lying in the same direction. Eddy-current testing has not only been demonstrated as an effective means of detecting such cracks (Navy, Department of 1980b), but it has also been shown to provide a means of evaluating crack severity (Anderson 1981). The detection of cracks by eddy-current testing may not be cost-effective in lieu of penetrant testing for many applications. However, in situations for which the surface has been protected with a thin coating or a relatively ductile metallic foil, cracks may not be open to the surface. In these instances, eddy-current testing may be used for both flaw detection and evaluation.

The production techniques for manufacturing graphite-reinforced aluminum yield a potential flaw that is ideally suited to eddy current detection and quantification. This flaw is caused by an incomplete bonding of adjacent precursor wires as the panel is formed. The result is similar to an unbond or delamination; however, instead of lying parallel to the surface, the defect lies in a plane perpendicular to the surface. Such a defect may have a significant effect on the transverse strength of the material, particularly if only one or two plys are used. In terms of eddy-current testing, such defects are similar to cracks in both their detectability and evaluation. Such defects are considerably less likely to be detected by ultrasonics or radiography (Navy, Department of 1981).

Eddy-current testing of discontinuously reinforced metal matrix composites such as SiC-Al has two separate purposes. One is to evaluate the severity of cracks that have been detected by other methods, such as penetrant testing. The other function is to verify a proper electrical conductivity over the specimen surface. The electrical conductivity of SiC-Al particulate or whisker composites is primarily affected by three variables: the volume percentage of reinforcement, the conductivity of the matrix, and the amount of microporosity. An anomalous conductivity measurement is thus always cause for further investigation. The ease with which such measurements can be made with inexpensive instrumentation further facilitates their utility as a quick check for the production of nonuniform or faulty material.

A significant benefit in the application of eddy-current testing to metal matrix composite structures is that many such structures have thin cross sections. As a result, eddy-current testing is often capable of testing the entire material volume.

Electrical Potential Testing

Electrical potential testing operates on the principle that electric currents are hampered by the presence of defects in the conducting medium. In this sense, electrical potential testing is similar to eddy-current testing. The major difference in the two techniques is that the electrical potential method produces currents through direct electrical contact, whereas eddy currents are produced inductively. Electrical potential testing can thus be accomplished with either direct or alternating currents.

The utilization of the electrical potential method for metal matrix composites has to date been limited to graphite-aluminum precursor wires. The objective in this case was to utilize a change in the electrical resistance as a means of detecting noninfiltration in the wire. Evaluation of such a wire testing device constructed by Materials Concepts, Inc. (Woessner et al. 1982) was conducted in conjunction with the testing of an acoustic device fabricated by Pennsylvania State University's Applied Research Laboratory (Reed 1982). The results of the comparison indicated that the acoustic method was more sensitive to noninfiltration of the precursor wire.

Magnetic Methods

To date, the material constituents of the major metal matrix composite systems have all been nonmagnetic. Thus, magnetic methods of nondestructive testing have not been applicable.

ACOUSTIC-MECHANICAL METHODS

The general approach whereby a material or object is made to vibrate and its resonance is studied is variously referred to as resonance testing, acoustic signature analysis, or vibrational spectroscopy, etc. It is typically applied at subsonic (Hz) and sonic (kHz) frequencies, but may extend to ultrasonic (MHz) frequencies for specimens of small dimensions.

In its most primitive application, an operator taps or otherwise sets into resonance a specimen and listens whether it "rings true." A more scientific and repeatable approach would have a controlled impact source, with vibration sensors for pickup and recording. Subsequent signature analysis of frequency and energy content could then be made to evaluate specimen quality. This approach has been studied in applications to both solids (Boricheva et al. 1979; Reneker 1978) and composites (Ramkur et al. 1979).

The underlying principle is that an object's or material's vibrational behavior is directly influenced by its stiffness or modulus. The modulus is in turn affected by the volume percent of fiber reinforcement, fiber orientation, and defects such as porosity, cracks, and delaminations. The presence of defect discontinuities such as these would give rise to a change in the vibration signature by dampening via frictional energy losses at the mating surfaces (Ensminger 1973; Schliekelmann 1972). Other types of defects, such as noninfiltration of fiber bundles, and density variations associated with fiber-rich or -poor regions, would also change the specimen's vibrational modes.

The low frequency resonance technique is to be recommended for wider application than is presently the case, especially as a complementary inspection tool. It is not limited to any one type of composite structure. One of its major strengths is that it is generally applicable to end-item inspection. A major limitation is that it may be difficult to isolate the cause and/or location of the defect. Equipment requirements are not extensive and are even negligible for some manual tests. On the other hand, many such tests are operator-dependent. To automate the inspection, the acoustic signature of each specimen size and shape would have to be determined for a base-line comparison. Finally, variations in specimen dimensions that are within specifications may cause significant changes in the signature.

In conclusion, resonance testing, even in its most rudimentary form of manual operation and subjective judgment, may provide useful information nondestructively. As signature analysis techniques are advanced and, in particular, automated, their correlation with material and structural performance will make this approach more valuable.

ULTRASONIC METHODS

Contact Inspection

Contact ultrasonic inspection is one of the most basic forms of ultrasonic testing and one of the most widely used industrial techniques for metals. The inspection is performed with an electronic instrument, usually referred to as a flaw detector, and a transducer designed for contact work. The electronic instrument contains a pulser to excite the transducer and a receiver, gate, and other controls to select sweep rate, gain, delay, and so forth. The received echoes are displayed on an oscilloscope, usually in a rectified, filtered, or video mode. This is the normal A-scan presentation. Flaws are detected by establishing a detection threshold using reference reflectors such as flat-bottom holes.

Contact inspection is widely used in metal-based industrial applications such as for nuclear piping and pressure vessels, oil and gas piping, and aircraft. Established methods for performing contact tests are revised and printed annually by the American Society for Testing and Materials (1981). Practices for contact testing are described in Part II of the ASTM Standards.

From basic principles, contact inspection should be as useful for MMC inspection as it is for metals. The constraints encountered in its application will be surface roughness and attenuation or scattering in the material.

As with immersion testing, the structure must be thick enough (for the frequency of inspection) that the front and back surfaces can be resolved. On thin, textile-type composites, contact inspection would not be feasible because of the rough surface and the front-back resolution problem.

The advantage of contact inspection is that the equipment is inexpensive and portable. The disadvantage is that it requires highly trained personnel to perform it; there are many variables in the technique--the transducer, the equipment itself, and the operator's judgment.

Contact inspection is a well-developed technique. Improvements in the technology are focused on improved transducers and electronics, in particular, using intelligent electronics to minimize the need for operator interpretation and the probability of operator errors.

C-Scan

An ultrasonic C-scan is a 2-dimensional representation or map of a material's properties derived from ultrasonic inspection. Most C-scans are similar to an X-ray in that they project a material's properties onto a plane. In practice, conventional C-scans are obtained by scanning a single transducer (echo) or a pair of transducers (through transmission) in an x, y Cartesian coordinate raster scan over the sample. Both sample and transducers are under water (or some other acoustic couplant). Either pulse or tone burst ultrasonic excitation is applied to the transducers. The measured signals represent the acoustic properties of the sample at the x, y coordinate location. For pulse echo, internal flaw depth may also be determined from the time of flight of the signal. For through transmission, the measured signal represents an integral through the material of the internal properties.

The acoustic material properties that can be determined with conventional C-scans are for the most part related to signal amplitude, i.e., attenuation or reflection. The reflected energy represents acoustic impedance changes in the material--generally cracks, but often subtle variations in acoustic velocity or material density. For material regions of high absorption, the complex impedance also leads to slight reflections. Material attenuation plays a major role in most C-scans. Acoustic energy is absorbed in the material (conversion to heat) or is scattered (altered propagation vector). In either case, the amplitude of the measured acoustic signal decreases.

Many successful applications of C-scans to composites analysis exist. In particular, C-scan techniques clearly show areas of disbond or anomalously high attenuation. Simple one-transducer pulse echo or pulse double transmissions are currently in use for composite examination in many laboratories. The double transmission technique uses a reflector plate (such as flat float glass) under the sample to return the acoustic energy to the single transducer.

These straightforward commercially available technologies can identify material regions of concern such as disbonds, delaminations, laminar cracking, and fiber density variations. The resolution of C-scans for these flaws depends on the acoustic wavelength versus flaw size and on the background acoustic "noise" present in the measured signal compared to the real change in acoustic signal.

The first factor represents effects of scattering. The scattering cross section or reflectability of a given flaw of size d falls off sharply as the acoustic wavelength λ exceeds d. The second factor depends on the amount of signal removed from the acoustic beam versus the variation in signal produced by amplifier noise and transducer noise. The effects of noise make interpretation of C-scans more complex than X-ray images.

In X-ray techniques the physics of the imaging method is related to the density of the material. In ultrasonic C-scan imaging, all the propagation properties may influence the image. In addition, the image is derived from an electrical signal, a transmitting transducer, a propagation path, the sample, a propagation path, and a receiving transducer. Thus the image is in some way interrelated with the entire system characteristics. The most complex link in that system is the transducer(s).

In addition to having limited bandwidths, transducers physically measure the integral of pressure over their surface. That does not represent the acoustic energy density in the wave. In fact, for many cases (the simplest being nonnormal incidence of plane waves), a transducer may output a zero electrical signal while significant ultrasonic energy is passing through its face. For measurements of material absorption, that represents significant noise or errors. Measurement artifacts of this type are worse for irregular, inhomogeneous materials such as composites.

Phase-insensitive measurement techniques are required for quantitative assessment of material attenuation. One such method involves phonon-electron drag in a piezoelectric photoconductor (CdS). Recent work with the device called an acousto-electric transducer (AET) has shown promise for composite materials (Southgate 1966; Busse et al. 1977; Heyman 1978; Busse and Miller 1981(a) and (b); Shoup et al. 1982).

New quantitative methodologies for C-scan hold great promise for improving the interpretation of the material state. Integration of scattering scans, nonlinear scans, and velocity profile scans, to name a few, into materials testing will provide materials scientists with significant information not presently available.

The thrust of C-scan research to improve the interpretation of composite material condition should be toward development of separable quantitative material maps. Having such independent maps available will allow reliable reading of ultrasonic NDE data with a degree of confidence based on physical principles. Examples of such maps would include the "normal" material attenuation, velocities, attenuation derivatives, scattering, and nonlinear response. Laboratory research to understand and develop a technological science base in these areas will provide real benefits for metal matrix composites NDE reliability.

Ultrasonic Velocity

An elastic wave propagates through a composite at a rate determined principally by its density, percent fiber reinforcement, and fiber orientation. The microstrain levels typically applied to materials in ultrasonic testing make the velocity measurement a useful nondestructive probe for both the evaluation of material properties and the detection of certain types of defects.

Velocity measurements are usually made by: (a) obtaining the transit time of an elastic wave pulse through the specimen or (b) obtaining the resonant frequency of vibration of the specimen (Truell et al. 1969; Ensminger 1973; and Williams and Lamb 1958). Other techniques employ combinations of the two basic methods, such as pulse overlap or phase-locked loop (Holder 1970; Heyman and Chern 1982). Wave frequencies commonly used extend from below one MHz to tens of MHz for the first technique and may extend down to the sonic range (kHz) for large specimens using the second technique. The resonant method finds its principal applications in thin specimens and rods. With both techniques, the specimen dimension in the direction of wave propagation must be known to calculate the velocity.

The basic relationship between ultrasonic velocity and material properties is that the stiffness or modulus is a function of the density and the propagation rates of the various wave modes. These modes include longitudinal (compressional), shear (distortional), surface, plate, and rod waves. The number of wave modes that contribute to a given modulus depends on the material symmetry, ranging from one to five modes in the case of a unidirectional composite. The generation of a particular mode is controlled by the method of wave excitation, the composite fiber orientation, and the sample dimensions relative to the wave frequency. Since defects such as porosity and fiber-poor regions affect the material density and stiffness, they also affect the velocity. This relationship between ultrasonic velocity and material properties may be applied to the following nondestructive needs in composites:

1. Determination of the engineering moduli, given the density (Blessing and Elban 1981; Read and Ledbetter 1977). The fiber modulus itself may also be measured by ultrasonic methods.

2. Detection of porosity (Blessing and Bertram 1979) and fiber-rich or -poor regions caused either by noninfiltration of fiber bundles or by irregular fiber spacing (Frost and Prout 1982; Anderson and Blessing 1979).

3. Evaluation of fiber orientation and residual stress (see section on nonlinear ultrasonics).

Furthermore, any other parameter that affects the material elasticity would be a candidate for evaluation by velocity measurements--for example, the effects of thermal excursions on fiber-matrix bonding (Blessing et al. 1980).

Some of the strengths or advantages that velocity measurements have for material examination are these: Velocity measurement techniques are well established, with up-to-date automated equipment available that is capable of very precise measurements. The transit time or resonant frequency of objects under inspection may be monitored simultaneously with echo amplitude measurements, providing a complementary tool for material inspection. In some cases, velocity (relative or absolute) measurements may be more easily related to material properties than scattering measurements.

Some of the weaknesses or limitations of this technique are the following: A precise measurement of velocity requires that the wavepath length--i.e., sample dimension--be known precisely. (Precise measurements are generally needed to minimize the propagation of errors in the calculation of the engineering moduli.) Composites possess complex modes of wave propagation that are difficult to analyze when the wave direction is not along a principal axis of symmetry. Finally, it should be noted that geometric dispersion, i.e., the velocity dependence on the ultrasonic wavelength and fiber size and spacing, may play a significant role in determining the material moduli (Blessing et al. 1980).

Ultrasonic Attenuation

Two of the basic causes of ultrasonic attenuation in material are hysteresis and scattering. In the frequency range of interest for the ultrasonic characterization of metal matrix composites, the relative magnitudes of losses due to hysteresis and those due to scattering caused by the fiber and defects are not yet established. There has been considerable theoretical work performed in the area of scattering over the past 50 years, with the earliest work dating back to Rayleigh (1929). Although most of the published work (Mason and McSkimin 1947; Mason and McSkimin 1948; Roth 1950; Huntington 1950; Papadakis 1960; Serabian and Williams 1978; Roderick and Truell 1952) on scattering in structural materials has dealt with the effects of grain size and microstructure on the attenuation, the theory may be directly applicable to the case of fiber- and particulate-reinforced composites.

The simplest attenuation measurements are made using a single transducer bonded to the specimen using reflection-mode ultrasonics. The display from a calibrated exponential generator is then fitted to the observed echo decay and the attenuation is read directly. If there are only one or two echoes available, a through transmission approach must be taken. One can compare the lossy material to an ideal "lossless" specimen, such as fused quartz, inserted between the two transducers and in series with a variable attenuator. The attenuator is adjusted to reduce the "lossless" signal to the level observed at the output of the lossy specimen, and the attenuation read is the direct signal lost on the first pass through the lossy material. A more direct, and perhaps preferable, method is to compare two thicknesses of the same lossy material. With this method, the change in signal completed is attributed to the change in specimen thickness, and hence the attenuation can be calculated. Buffers are generally used in direct contact methods to enable one to separate the transducer electrical response from the specimen response when taking attenuation measurements as a function of frequency. Sources of spurious attenuation include specimen nonparallelism, phase cancellation errors, and diffraction losses arising from beam spread.

The experimental use of ultrasonic attenuation to characterize composites is quite widespread, with C-scan ultrasonic methods being one of the most common inspection methods. However, a conventional ultrasonic C-scan, where the amplitude loss greater than a preset value is printed white and all amplitudes less than that value are printed black, is not quantitative. On the other hand, quantitative attenuation measurements can provide information about the physical mechanism giving rise to the attenuation loss.

There have been few quantitative attenuation measurements reported in the literature on composites. Stone and Clark (1975) examined attenuation as a measure of void content in graphite-epoxy, while Vary and Lark (1978) and Hayford et al. (1977) have correlated attenuation with the mechanical properties of graphite-epoxy composites. Shoup et al. (1982) produced two-dimensional images based on the frequency-dependence of the ultrasonic attenuation to characterize the results of impact and fatigue damage in graphite-epoxy composite laminates. The future potential of ultrasonic test methods based on attenuation is promising. However, significant basic research (both experimental and theoretical) is required to establish the relationships between ultrasonic attenuation data and composite material defects and properties.

Nonlinear Effects

This summary is included to describe a new field of acoustics that may have application to metal matrix composite NDE. In general, the use of ultrasonics to characterize material consists primarily of 3 measurement areas: attenuation (absorption and scattering), sound velocity (both group and phase), and material "impedance" measurements (both a material property and a "flaw property").

These 3 categories are not independent, since velocity, absorption, and impedance are linked through transformation equations. However, most NDE specialists consider these as separate measurement categories. A more subtle division exists in the field of physical acoustics for large displacement amplitudes (or highly nonlinear materials). That area, called nonlinear acoustics (NLA), may play an important role for some examinations.

As a brief review of NLA, we consider a simple model of a solid consisting of springs. The response of the model to small forces is a linear displacement--that is, stress is equal to a constant times strain. For large-amplitude displacements, we must include higher order relationships (moduli or elastic constants) to obtain a non-Hookeian (nonlinear) response from the material. Thus, the material "stiffness" depends on the strain--it may increase or decrease depending on the sign of the higher order modulus, M_3.

M_3, and more accurately all the third-order elastic constants, tells us about material properties perhaps as important for NDE as the normal second-order elastic properties (i.e., Young's modulus). For example, recent work by Heyman and Chern (1981) has shown that heat treatment of aluminum affects higher order elastic properties more than it affects second order elastic properties. Thus, for some materials, measurements of sonic velocity may reveal little, whereas measurements of velocity derivatives (such as with respect to temperature or stress) are more revealing.

Continuing with our simple model, to show how the higher order terms affect sonic measurements, we evaluate the acoustic velocity. The square of the velocity is related to the ratio of the material modulus and density. For the case of a linear displacement, the velocity derivative with respect to strain is zero. Thus the sound velocity does not depend on strain for this simple case. For the non-Hookeian case, where the modulus is strain-dependent, the sound velocity is linearly related to the strain. All conventional materials exhibit a nonzero M_3 and fall into this category. A comparison between linear and nonlinear analysis shows that, for a material with nonzero higher order elastic constants, the sound velocity will depend on the material strain--a potentially useful result for NDE. Applications of this are already being made in the area of bolt tension (Heyman and Chern 1982).

Other measurements are available that are related to the material nonlinearity. For example, if a periodic driving force is applied, a single periodic displacement will result. If, on the other hand, a nonperiodic force is applied, a more complex response will occur. Thus, higher harmonics of the fundamental periodic force will occur. This form of measurement is appropriately called harmonic generation and is usually measured as the ratio of the amplitude harmonic to the fundamental amplitude.

There are many physical properties associated with NLA. The following examples of such properties are given with a reference chosen to suggest the type of analysis possible for each category. There is, of course, much outstanding work in each area that is not mentioned here.

- Harmonic generation (Green 1973; Thurston and Shapiro 1967; Thompson and Tiersten 1977)
- Stress (or strain) velocity derivatives (Heyman and Chern 1982; Heyman 1977; Hughes and Kelly 1953)
- Thermal velocity derivatives (Salama and Ling 1980; Chern et al. 1981)
- Elastic constants (Green 1973; Thurston and Brugger 1964; Gauster and Breazeale 1968)
- Amplitude-dependent absorption (Richardson et al. 1968)
- Elastic-wave static displacement (Cantrell and Winfree 1980)
- Shock-wave response in solids (Brugger 1964)
- Absorption (phonon-phonon interactions) (Akhieser 1939; Woodruff and Ehrenreich 1961)
- Thermal conductivity (Ashcroft and Mermin 1976)

The foregoing properties are a result of physical characteristics of the material. A form of nonlinearity may exist in a material caused by material geometry. The most usual case of this is the crack. Under compression, the crack behaves as the host material. However, under tension, the stress/strain curve near the crack exhibits a different slope than the host. Such a sharp discontinuity in the stress-strain curve produces strong harmonic generation.

Other geometrical effects include enhanced resolution in ultrasonic microscopy accompanying the generation of higher harmonics and the resulting shorter wavelengths:

- Harmonic generation at a crack (Morris et al. 1979)
- Resolution enhancement through harmonic generation (Kompfner and Lemons 1976)

There are many aspects of metal matrix composites yet to be determined. The use of NLA may play a significant role in characterizing the mechanical behavior of these materials. In addition, the variation of material properties (i.e., flaws) may be more easily detected via "higher order imaging" of materials properties. For example, in boron-aluminum composite matrix material, fiber separation from the matrix may result in a significant harmonic generation source. Even though the separation may be significantly less than a wavelength, it is detectable through its harmonic "signature."

More vigorous measurements would include determination of the higher order elastic constants associated with the principal symmetry axis of the ply stacking sequence. The flat plate geometry may require that combinations of 3rd order elastic constants be evaluated. Such measurements may reveal how well the fibers are linked to the matrix.

In addition to the traditional NDE techniques including ultrasonics, NLA methodology holds many potential benefits for advanced materials characterization. Additional effort in this research area is welcome and timely.

Imaging

Pulse Echo Ultrasonic Imaging

The concept employed in pulse echo imaging is an extension of the technique of ultrasonic C-scanning. As with C-scan imaging, an x, y scanner moves the ultrasonic transducer over the surface of the part being inspected in a raster scan pattern. At increments along the scanned direction, the transducer is pulsed from the ultrasonic instrument, which causes a sound burst to be transmitted into the material. The echo from the front surface and the back surface is then recorded. If flaws are contained in the interior of the piece, the echoes from such flaws also show up in the time waveform of the received echo. For each x, y position, the acoustic signal processor generates two ultrasonic parameters. The first parameter is the time of flight, or the time interval between the front surface echo and the echo from interior flaws in the piece. The second parameter is the amplitude of the echo in the back surface gate, which is also transmitted to the digital memory. Hence, as the scan is being made, the information is displayed in a gray-scale fashion on television monitors. One monitor shows the intensity of the received signal and another shows the time of flight. To generate an isometric or pseudo-three-dimensional image of the structure, the information is read out of the digital memory at video rates into an isometric image processor. The image processor takes the x, y, time of flight, and amplitude information and performs tilt and rotate operations in analog electronics to provide x, y and z information. This is then displayed on an x, y monitor. That form of display will show a front surface and a back surface and intermediate flaws or defects in an isometric perspective view. By adjusting the dials on the isometric image processor, the image can be tilted, rotated, or expanded to obtain more informative views of areas of interest.

Ultrasonic imaging has been shown to be an effective method for characterizing defects in both metals and organic matrix composites (Becker et al. 1979; Frederick et al. 1979; Nuclear Regulatory Commission n.d.; Barbian et al. 1980; Moore and Dodd 1982). There are no physical considerations that would intrinsically limit similar usefulness for metal matrix composites. Several studies demonstrated the usefulness of the concept in characterizing impact and fatigue effects in graphite-epoxy materials (Pettit 1979; Shoup et al. 1982; Thomas et al. 1982). Other investigators (Sheldon 1978) have used isometric imaging successfully to examine composite aircraft structures.

Ultrasonic imaging should be applicable, in general, to inspection of MMC structures. Certain factors that affect its usefulness are the intrinsic attenuation of the material, the thickness of the structure, and the natural scattering or acoustic noise caused by the internal structure of the material.

The advantages of pulse echo ultrasonic imaging in nondestructive testing are the speed of the image presentation, and the ability to obtain pseudo three-dimensional imaging without extensive or time-consuming processing. The composite B-scan and C-scan (i.e., isometric image) presentation provides both depth and size information. There are, however, limitations or restrictions on the application of this technique: On a very thin material, one must be able to resolve the front and back surfaces in order to obtain information on interior flaws. This creates the need for using high-frequency ultrasound to obtain a very short wavelength. Depending on the attenuation of the material, the use of higher frequencies may not allow sufficient energy to be transmitted through the material to obtain a usable signal. So one must balance the simultaneous constraints of thickness of the piece with the frequency that can penetrate it. Hence, one must evaluate in a given application the priority of information and also the ultrasonic attenuation of the material being tested. Another disadvantage is that it is an amplitude-dependent technique that relies on direct reflections from the internal flaws to create the ultrasonic image.

Textile fiber systems pose a special problem for ultrasonic imaging. If the fabric is too thin to allow the front and back surface to be resolved, then it will not be possible to obtain an isometric image. If the structure is inspectable, then the variation in front surface location can be compensated for by using a surface-following gate.

There should be no inherent or peculiar problems involved in applying this technique to monofilament or particulate types of composites.

Research and development in pulse-echo imaging are aimed chiefly at two areas: increased speed through use of linear array transducers (Becker et al. 1979) and increased detection and resolution through signal processing techniques such as the synthetic aperture focusing technique (SAFT) (Frederick et al. 1979; Nuclear Regulatory Commission n.d.) and amplitude and time-of-flight locus curves (ALOK--German acronym) (Barbian et al. 1980, Moore and Dodd in press). Both the SAFT and ALOK techniques integrate and utilize information gained over a larger aperture to form the image, whereas C-scanning and simple pulse-echo images utilize only the information gained at each point without regard to neighboring measurements. Hence, the SAFT and ALOK techniques are more precise and less subject to influence by coarse-grained or highly scattering materials.

Scanned Acoustic Holography

Scanned acoustic holography uses ultrasound to create an interferogram or hologram of the specimen being tested. As with ultrasonic pulse echo imaging, the transducer is scanned over the part being tested. In pulse echo imaging, the transducer is focused in the area of the flaw to achieve optimum resolution. With ultrasonic holography, however, very diffuse insonification of the interior of the piece is desired, and hence the focal point of the transducer is typically placed on the surface of the part. As the burst of ultrasound enters the material and is reflected by an internal defect, an echo is received back at the transmitting transducer. The returned echo signal is interferred with electronically by a reference beam that is in phase with the transmitting transducer. The phase difference data or hologram is stored in digital memory. The hologram is then computer-reconstructed using backward-wave techniques or Fresnel reconstruction techniques. This gives the operator great flexibility in examining the ultrasonic information. Under computer control, the operator can examine the images a layer at a time from the top surface, stepping in increments from the front to the back surface. At each depth, the operator can see what defects come into focus.

In coherent holography, a burst of single-frequency ultrasound is used to investigate the structure. An alternative to this is time-of-flight holography, in which a short broadband signal is used. The phase of the returned echo is derived from the time of flight by using a synthetic frequency. Time-of-flight holography offers better depth resolution than coherent holographic techniques.

Acoustic holography is being used in industrial work, especially in nuclear applications (Becker et al. 1979), where systems for inspection of pressure vessels and piping have been developed. Holography has also been applied to organic composites (Sheldon 1978). The use of holography is becoming more widespread since the advent of high-speed computers has made digital reconstruction possible.

Acoustic holography should be generally applicable to metal matrix composites. The geometry (size, roughness) will be a more important restriction than the matrix or fiber type. However, any thin material, such as woven fiber textile types of MMC will not be inspectable by holography, whereas, the vacuum-infiltrated textile materials that are thicker (1.0 in. or more) would be inspectable by holography.

The general advantage of ultrasonic holography is the increased resolution that is achievable through this technique. By using array processors and digital computers, a reconstruction of an acoustic hologram can be obtained in a few minutes. This allows near-real-time generation of the ultrasonic images that provide optimum resolution of the details of the reflectors. The great benefit of holography is in inspecting thick materials where it is not possible to focus a transducer through the depth of the part. For example, an aluminum plate that is 4 in. thick is equivalent to a 16-in. water path. For a focused transducer to have an adequate F number, such as F4, would require a 4-in. diameter focused transducer. But with ultrasonic holography it is the area of the scanned aperture versus the depth of the structure that determines the F number and hence the resolution of the ultimate image; thus one avoids having to use unreasonably large transducers to achieve high resolution. Furthermore, because of the ability to obtain an image at greater depths, holography can be used on thicker structures.

Areas of development being pursued for scanned acoustic holography are aimed at computer reconstruction of images and integration of information from several scans into a single image. For example, the images obtained from ±45° shear wave scans and a normal-incidence longitudinal scan can be combined into a single image. This provides more complete information on the geometry of the reflector or defect being investigated.

Because of the availability of high-speed computer processing, the holographic technique has a high potential as a useful inspection tool for thick-walled structures.

Liquid Surface Holography

The concept of liquid surface holography is to use an object beam transducer that provides a coherent burst of ultrasound that is transmitted through the part or specimen being inspected. As it travels through the piece, internal reflectors, differences in velocity, etc., cause the wavefront to be distorted in phase. The ultrasound is focused through an acoustic lens and then passes through an ultrasonic window into another tank. At that point, an additional lens recollimates the ultrasonic beam. The sound is then reflected into a vertical direction, where it impinges on a specially constructed membrane. This rubber membrane is levitated by the pressure from the incident ultrasound. At the same time, a reference transducer illuminates the liquid surface area. The reference beam is in phase with the object beam, and so it provides an interference pattern on the liquid surface with the object beam. Hence, with each burst of sound transmitted from the object beam, there is a new hologram created on the surface of the membrane. To get a real-time reconstruction of this image, laser light is sent through a collimating lens to the hologram, which in turn acts as a diffraction grating to the coherent light. The first-order diffraction information contains the reconstruction of the hologram. The diffracted beam is focused through the collimating lens, back to the prism, through a spatial filter, into the imaging lens and recording system. In this way a real-time image of the transmissivity of the object being inspected is obtained.

An important advantage of liquid surface holography is that it is a real-time system. It is especially well suited for inspection of large quantities of goods, particularly those where inspection time must be minimized. Such a system is suitable for a production environment of tubes, plates, sheet material, or any other type of structure that can be immersed in a water bath in a reasonable fashion. A disadvantage of the system is that it is a through-transmission technique and requires that the object be submerged in a water tank; another disadvantage is that the technique is not as sensitive as scanned acoustical holography (American Society for Metals 1976).

One natural artifact in a liquid surface holographic image is the superposition of the near field pattern of the object beam in the ultimate image. By mechanically wobbling the object and reference beams and then frame averaging, these anomalies can be removed. With the use of advanced electronics, these aberrations can be removed by computer image processing.

The real-time aspect of the technique makes it useful for inspecting large areas of textile-type materials. Areas that are not completely infiltrated by the matrix material will show up distinctly in the image. The method can be applied to either flat or cylindrical objects. In cases where sensitivity requirements are not stringent but speed and throughput are, this technique offers definite advantages and potential.

The emphasis in development of liquid surface holography is in improving the image quality by removing inherent artifacts. As mentioned earlier, a fringe pattern of light and dark bands is naturally superimposed on the image. Research effort is being pursued to eliminate these artifacts with frame-averaging techniques. The use of fast digital scan converters allows one to maintain the high inspection rate while still reducing unwanted artifacts in the image.

SUMMARY

Nondestructive evaluation of materials has as its origin the need to ensure the expected performance of materials. While early techniques were qualitative in character, today's increased performance demands have created the need for more quantitative as well as more reliable materials characterization. The field of nondestructive evaluation matured during the development of metals and other homogeneous materials, in which relatively simple crack-like discontinuities frequently represented the target of such evaluation. In contrast, composite materials which are inherently inhomogeneous and anisotropic, fail by composite mechanisms. Hence, previously developed NDE methods are not adequate to characterize these more complex materials. For composites to achieve their full potential of enhanced performance in advanced applications, NDE methods tailored to their unique features must be developed.

The application of NDE methods to metal matrix composites is in its infancy. Efforts at nondestructive evaluation of metal matrix composites have been limited primarily to commercially available approaches such as dye penetrant, ultrasonic C-scan, and X-radiography. Advanced NDE methods that appear to hold promise have not yet been applied. The complexity of these materials suggests the need to develop measurement techniques appropriate not only for the study of metal matrix composites in general but perhaps also optimized for the investigation of specific combinations of fiber and matrix.

Because of practical limitations of analytical models, NDE technologies rely on the development of an empirical data base. Future applications of metal matrix composites will be enhanced by obtaining quantitative relationships between material behavior and measured NDE properties. Relatively few reports of such a nature exist--highlighting the need for improving this science base. The ideal time to develop such a data base is concurrent with the development of the material itself. In that way the generation of the NDE data base may reduce the total time necessary to bring the material to use. This integration of the development of NDE methods with the development of the materials themselves will ultimately result in materials that are practically and economically inspectable, facilitating the development of in-process inspection and control.

RECOMMENDATIONS

In summary, the following actions are recommended:

1. Development of methods for nondestructive evaluation tailored specifically to the characterization of metal matrix composite materials.
   - o Develop a fundamental science base relating quantitative physical measurements to material properties and behavior.
   - o Develop techniques and instrumentation that apply this science base to these anisotropic, heterogeneous, and geometrically complex MMC structures.
   - o Develop reliable automated means of data collection and interpretation.
2. Integration of the development of methods for nondestructive evaluation with the development of the MMC materials themselves.
   - o Incorporate the application of advanced NDE methods early in the design and development of new material systems.
   - o Incorporate NDE inspectability in the design of new structures.
   - o Generate an NDE data base during material/structure life cycle testing.

   This interaction between development of fabrication procedures and NDT methods should continue until both are finalized.

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Chapter 3

MANUFACTURING TECHNOLOGY

This chapter is concerned with defects induced during the manufacture of MMC materials and structures. Steps involved in the various MMC manufacturing processes and the defect types related to each processing step are outlined.

The material defects and anamolies described here represent most of the observed forms. As the manufacturing technology evolves, many of these defects will be precluded from production material. Hence, these defects should not be judged to be typical of post-development materials.

There are three major types of reinforcements considered here:

1. Continuous Monofilament
    - silicon carbide (SCS-2, SCS-6, "standard" SiC)
    - boron
    - B_4C coated boron (B_4C-B)
    - SiC coated boron (BorSiC^{TM})
2. Discontinuous
    - SiC particulate
    - SiC whisker
3. Continuous multifilament yarn
    - carbon fiber yarn
    - Al_2O_3 fiber yarn
    - "SiC" fiber yarn

Although a large number of alloys have at various times been incorporated into composite structures, at present we concern ourselves with Al-, Ti-, and Mg-base alloys.

Each reinforcement by its nature demands a specific fabrication process, with predetermined limits of fabrication parameters (e.g., temperature, time, pressure, atmosphere). The texture and detail of these parameters as well as the processing of the basic materials determine the defects characteristic of a given composite article. The manufacturing processes include diffusion bonding, hot molding, powder blending, forging, HIP consolidation, casting, pultrusion, extrusion, and rolling, and often combinations of these.

This chapter is subdivided according to the form of the fiber (discontinuous, continuous monofilament, continuous multifilament yarn). The manufacturing process for each specific system or class of systems is described in each section.

DISCONTINUOUS REINFORCED MATERIALS

In the area of discontinuous reinforced MMC materials there are two principal suppliers, DWA Composite Specialties and ARCO Metals Silag Operations. Both incorporate silicon carbide as the reinforcement medium, with DWA using a particulate form and Silag primarily using a whisker form. Both show impressive modulus increases with relatively modest reinforcement volume fractions. An example of reinforcement volume fraction versus modulus increase is shown in Figure 1(a) for one of the Silag materials.

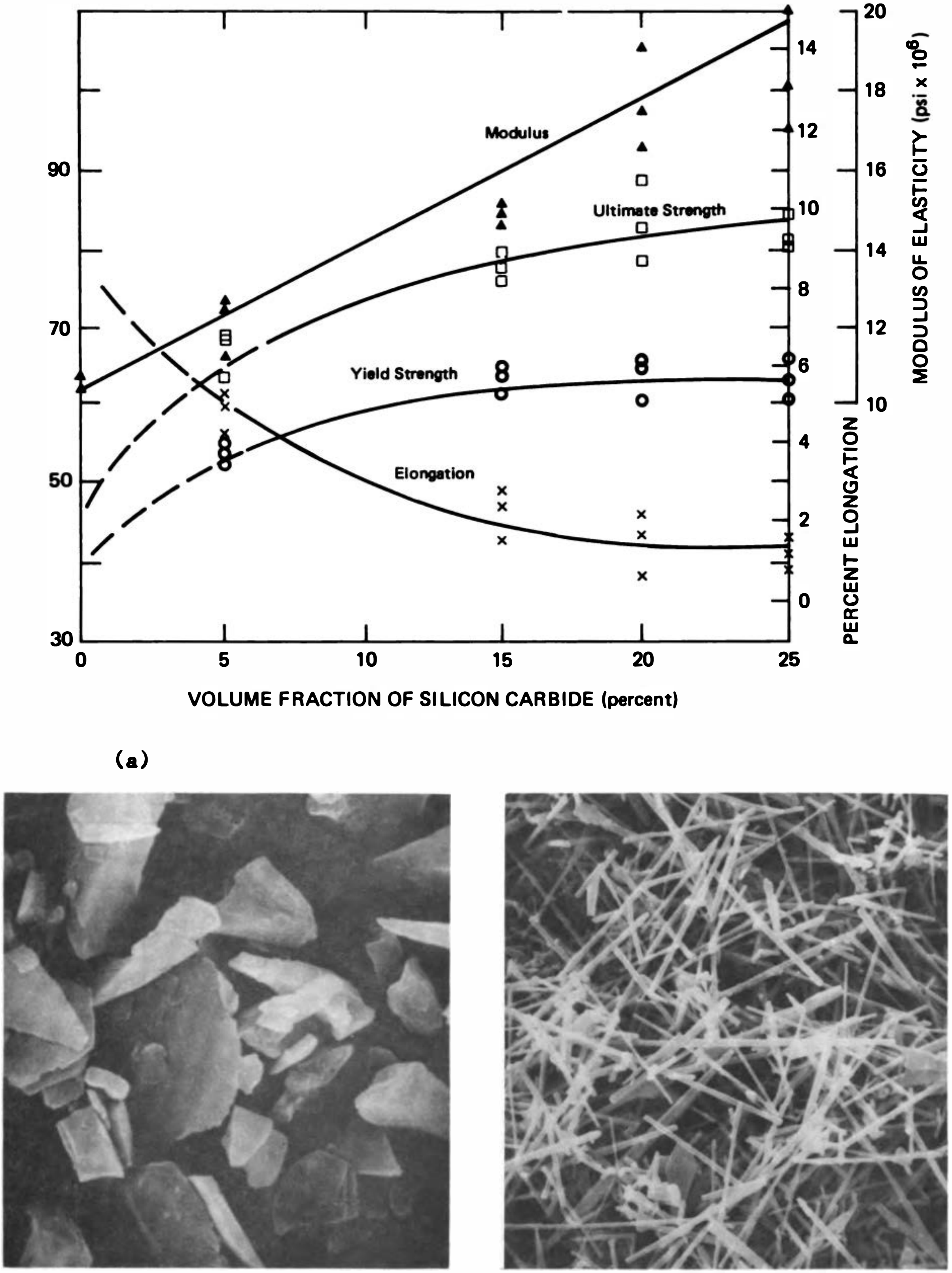
The reinforcement material in both systems is silicon carbide, but the approach is quite different. At DWA the silicon carbide is in the form of grinding "grit," the same basic material used in high-speed grinding wheels. Various sizes of grit have been explored, with the current sizes nominally 80 to 100 mesh [Figure 1(b)]. In the Silag material system, the SiC reinforcement material is produced by a coking and gaseous conversion process from rice hulls. The result is a whisker-like fiber of high length-to-diameter ratio and of extremely small diameter (1 μ diameter with L/D from 50 to 100) [Figure (1c)].

Consolidation

The basic steps for manufacturing the current generation of discontinuous metal matrix composites follows the flow chart in Figure 2. The basic steps are as follows:

1. The first consolidation operation is the blending of the constituent material. The metal powder and the whisker or particulate material are subjected to a mechanical mixing step to ensure a uniform blending of the constituents. This operation is usually done in an inert environment to preclude problems with the explosive powder mixtures. Liquid blending agents have also been used successfully; they aid in breaking up agglomeration of reinforcement that could create matrix-lean areas.

2. After the blending operation the mix is poured into the desired pressing preform shape. Currently, with the silicon carbide-reinforced aluminum, the preformed shapes are round billets or square "pancake" billets. The pressing is accomplished in a vacuum; the current aluminum alloys are pressed above the solidus of the matrix alloy. Pressure levels for the aluminum at this temperature can reach over 2,500 psi; therefore,



(b) Standard SiC Powder (4000 X)

(c) Submicron SiC Whisker (1500 X)

FIGURE 1 Silag composites of varying volume fractions (courtesy of ARCO Metals, Silag Operations).

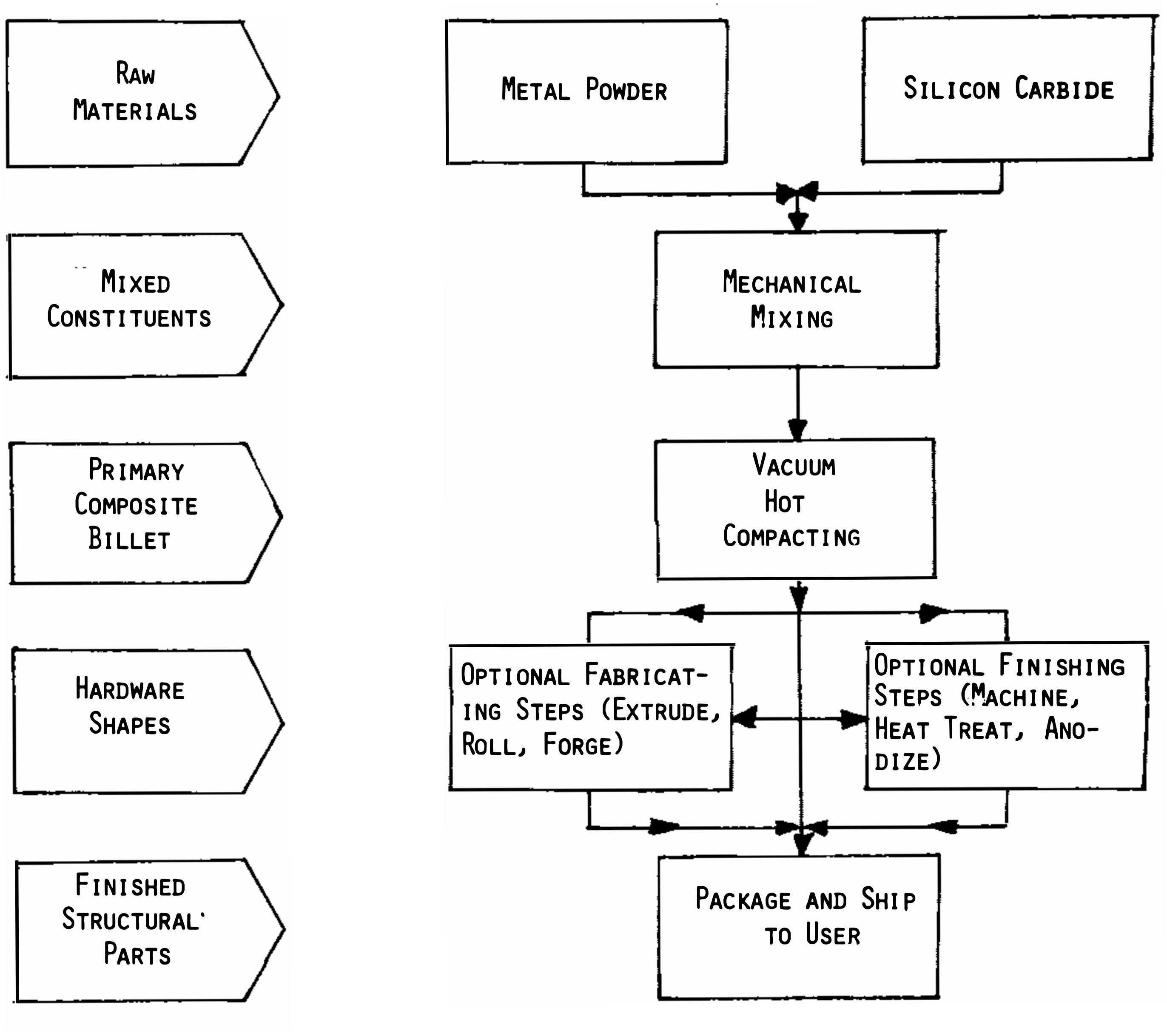


FIGURE 2 Flow of processing for SiC-reinforced aluminum (courtesy of ARCO Metals, Silag Operation).

sizable presses are necessary to make production quantities of these materials. As of this writing the largest billet sizes produced have been in the 150-pound range; however, both suppliers have ongoing billet size expansion plans.

Metalworking

The metalworking steps subsequent to the compaction cycle are comparable to what can be done with conventional aluminum alloys, except that additional precautions must be used that take into account the low ductility and high flow stress of the reinforced material. Currently under way are development efforts to produce rolled sheet and plate, extrusions, and forged parts from both the whisker- and particulate-reinforced aluminums.

The rolling of sheet and plate product forms from the initial compacted billets is currently under development by the two main material producers. Initial results have shown that current alloys can be rolled, but a new schedule must be developed for rolling preform preparations, rolling temperatures, reheat cycles, and per-pass reduction levels. The low ductility and high flow stress in these materials produce a high degree of edge cracking and potentially high scrap rate.

Process development efforts are continuing, and results to date would indicate that a high-quality rolled product will be forthcoming. By using an extrusion process, the materials have been worked into various product forms. Initial plate forms were made by extruding the billet materials through a rectangular die. Another process using a back-extrusion technique has produced the cylindrical parts of DWAL 20 material (Figure 3). Again, as in the rolling process, the temperatures and pressures used are considerably changed from the matrix alloy parameter.

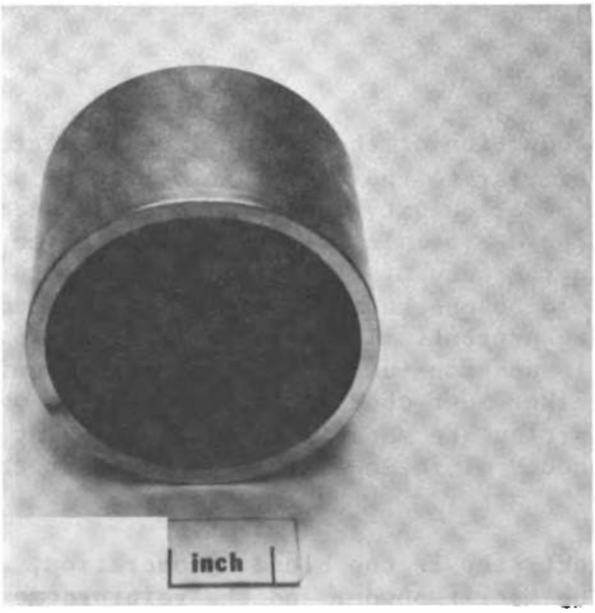


FIGURE 3 Extruded cylinder of 25 v/o SiC/6061 aluminum (courtesy of DWA Composite Specialties).

Forgings are another metalworking process adaptable to the discontinuous reinforced materials, although the same materials considerations of low ductility and high flow stress must be taken into account. The results, however, have proved successful to date, as shown in Figure 4 when the forging parameters are changed to compensate for the unique materials behavior.

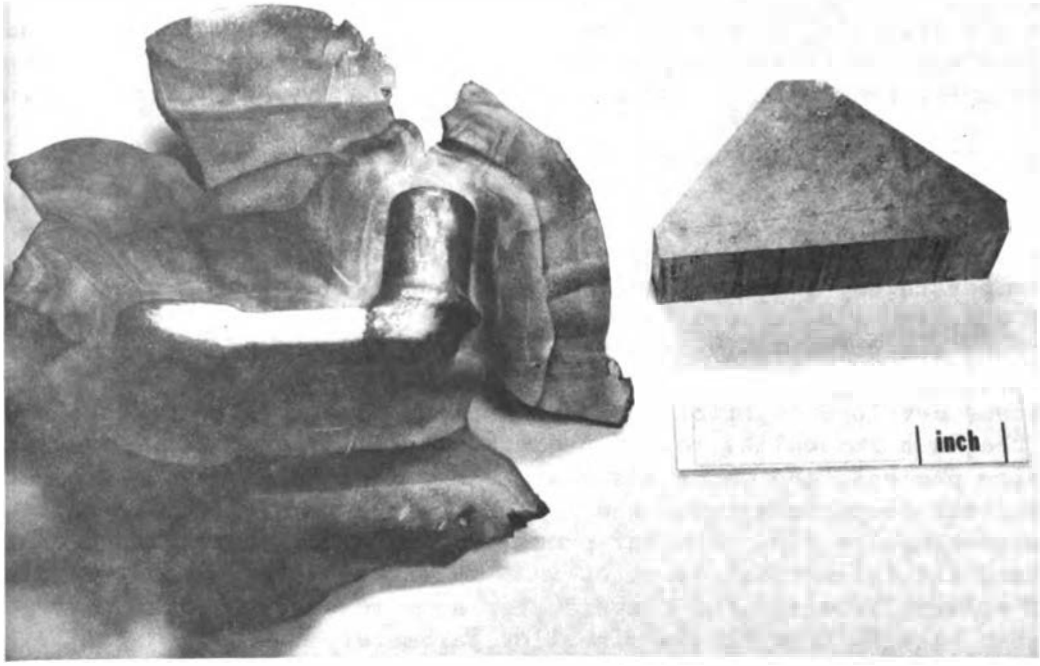


FIGURE 4 Forging of 25 v/o SiC/6061 aluminum (courtesy of DWA Composite Specialties).

Flaw Identification

The production of the discontinuous reinforcement material follows procedures similar to those used in producing powder aluminum billets, and therefore similar quality control checks are necessary. Chemical and sieve analyses of powder samples can determine if the powder is of acceptable quality. In the case of the reinforcement materials, the particulate material could be checked by a sieve analysis to make sure no oversized particles are present. The whisker material appears to require a more subjective inspection--usually microscopic examination. The current F-9 grade of whisker must contain over 80 percent whiskers, with the remainder being SiC particulate material. Close scrutiny of the quality of the input materials should minimize flaws or defects at this point in the fabrication (Figure 5).

The next step is the blending operation, which is a prime source of defects. The matrix powder and the reinforcement material must be thoroughly mixed to preclude agglomerations of reinforcement material and thereby matrix-lean areas. Figure 6 shows an ultrasonic scan with areas of suspected poor blending. These matrix-lean areas would promote crack initiation because of the resultant low ductility.

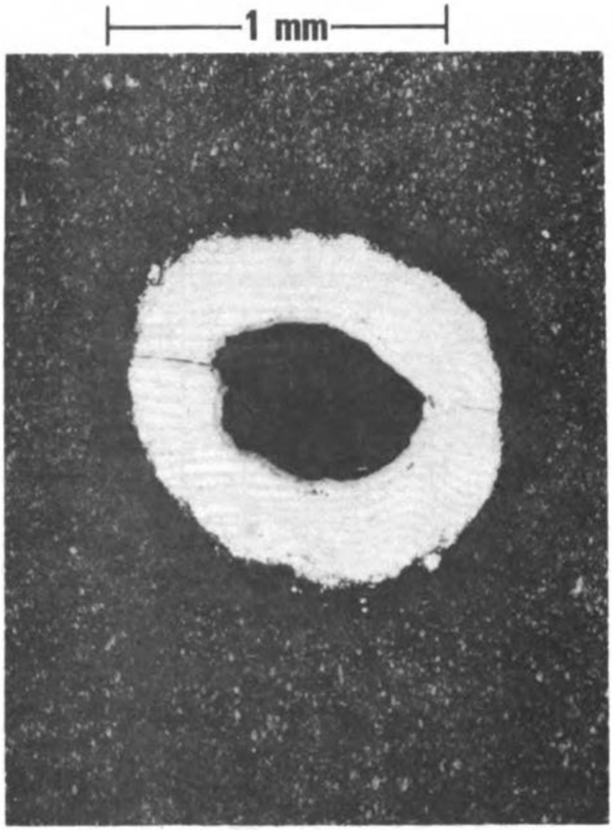


FIGURE 5 Metallic inclusion in silicon carbide-reinforced aluminum (Source: Naval Surface Weapons Center).

In the billet consolidation, the nominal density attained is 98 percent of theoretical. This by inference means a possibility of a few percent porosity in the material. These voids typically show up in the billet form, and secondary processing should reduce or eliminate them (Figure 7).

In all subsequent metalworking, such as rolling, extrusion, and forging, the metal matrix materials should respond in a fashion typical of conventional aluminum alloys. The MMC materials have reduced ductility and increased flow stresses, which must be taken into account when determining processing speeds and feeds.

In one area of metal joining--fusion welding--the MMC materials exhibit behavior considerably different from neat aluminum. Because of the enhanced high-temperature capability from the SiC reinforcement, the material does not flow in a weld joint. As shown in Figure 8, the weld metal and the base metal are not mixed in any way, so the weld is actually more typical of a brazed joint.

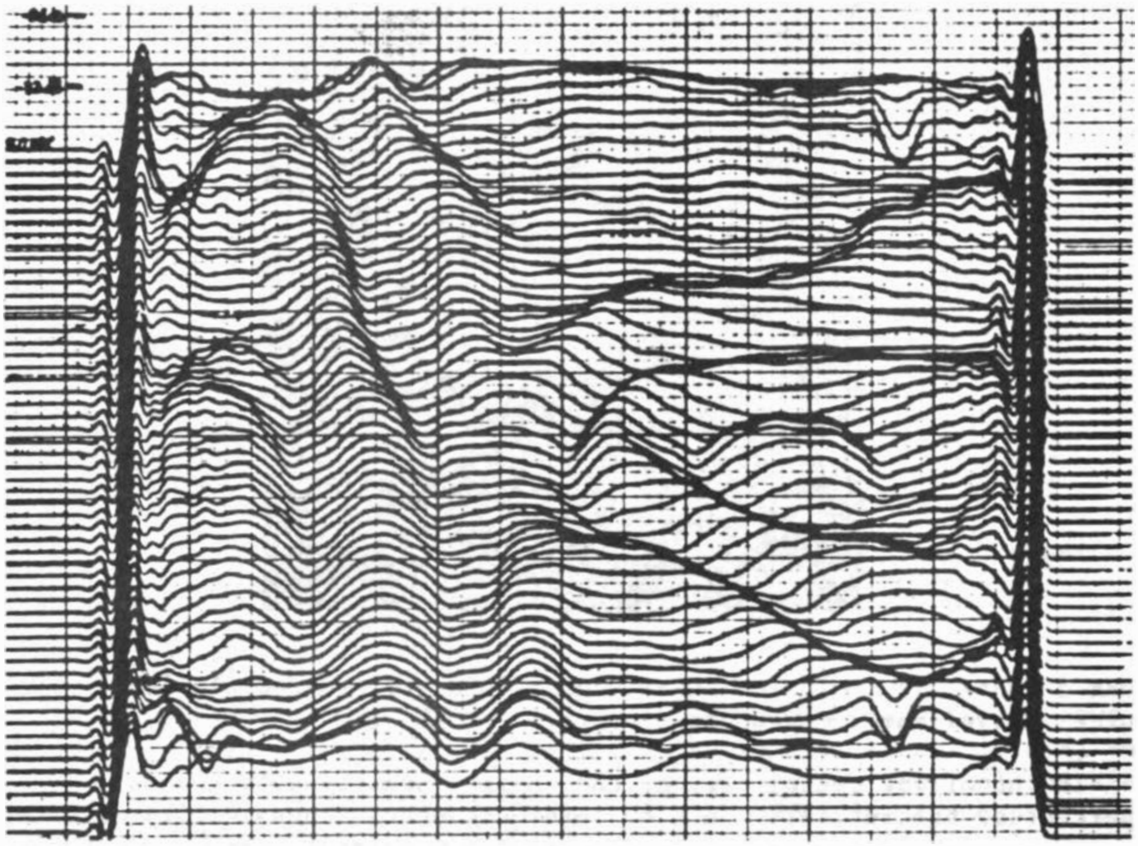


FIGURE 6 Ultrasonic through-transmission scan showing areas of suspected agglomeration in SiC/6061 aluminum plate (courtesy of Naval Surface Weapons Center).

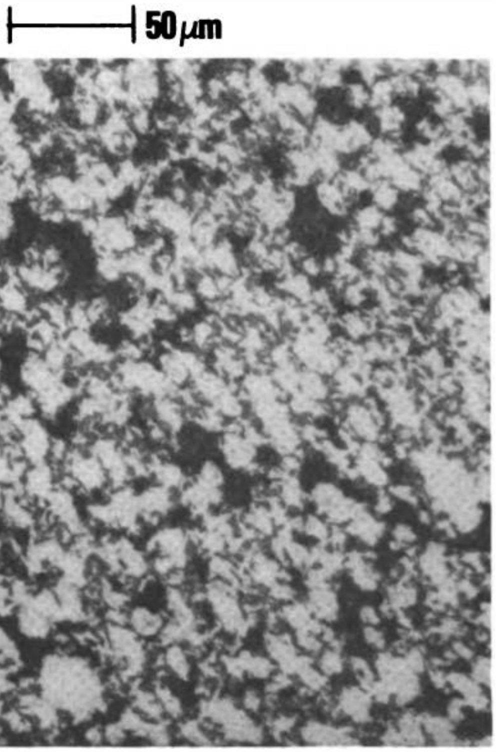


FIGURE 7 Porosity in silicon carbide reinforced aluminum. Void percentage 10% (courtesy of Naval Surface Weapons Center).

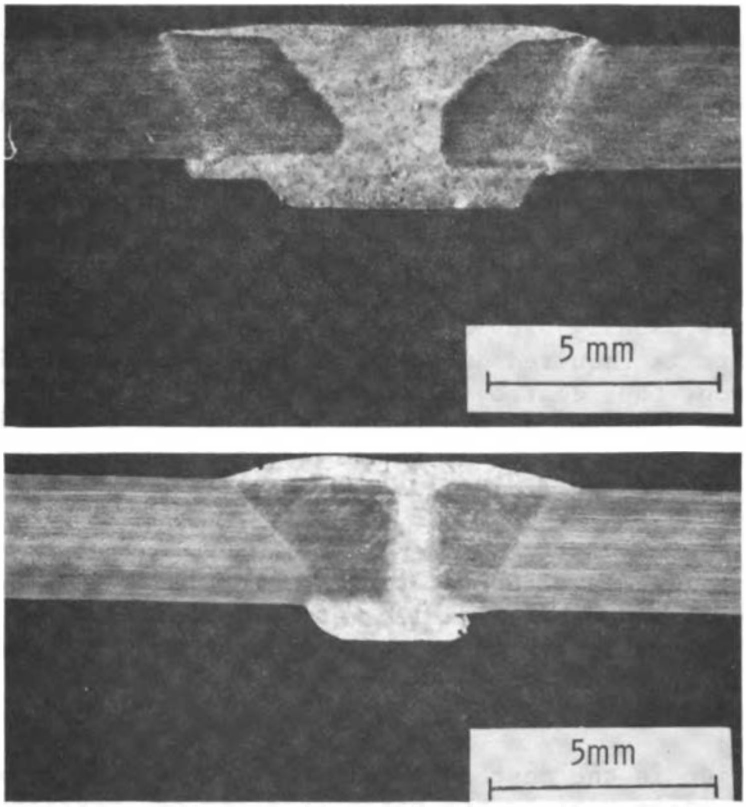


FIGURE 8 Weldments of SiC reinforced aluminum showing little flow (Photo courtesy of Martin Marietta Labs, from Ahearn et al., Metal Construction 14:192-7).

CONTINUOUS MONOFILAMENT REINFORCED MATERIALS

Diffusion Bonding (Boron/Aluminum)

Diffusion bonding is defined as a solid-state consolidation process involving temperature, pressure, and time. The process was developed for B/Al but is used with minor variations for SiC/Al, B_4C/Al, and BorSiC/Al. It is also used for SiC/Ti, B_4C/Ti, and BorSiC/Ti.

The basic process as developed for B/Al is shown in Figure 9. This process is identified for the production of monolayer MMC tubes (discussed later) or the manufacture of multi-ply panels at various ply orientations.

The steps involved are as follows:

1. Drum winding--The filament is level-wound onto an aluminum-foil-lined drum at a precise filament spacing to provide basic orientation of the filament. During or just after winding, polystyrene or acrylic adhesion is applied to fix the filaments into place. (These are low residual binders if outgassed in vacuo.)

2. Ply cutting and lay-up--The drum wrap, preform, or "green tape" consists of solvent-cleaned aluminum alloy foils, wrapped filament, and binder. The preform is sliced and removed from the drum, cut into the ply pattern, and stacked with the appropriate foils interleaved to give the desired final volume fraction.

3. Vacuum bagging--The lay-up, including stop-off-coated separating sheets, is seam-welded inside sheet steel. A vacuum port is then attached. Clamping pressure is continually applied to prevent misalignment of the lay-up.

4. Binder removal and outgassing--The polystyrene or acrylic must be removed before consolidation; in addition, a number of binders in the stop-off materials must be removed to prevent contamination. Binder removal takes place by heating to 750-800°F while dynamically evacuating. The heat for outgassing is usually provided by the platens of the hot press. Positive pressure is required during this step to prevent shifting of the filament position, thus destroying the uniformity of spacing of the lay-up. The compliance of aluminum alloys tends to result in a cradling of the filament during wrapping. Hence, the pressure of atmosphere acting through the vacuum envelope is sufficient to prevent filament "swimming" in aluminum matrix alloys.

"Stiff" matrix alloys such as titanium require higher pressure during the binder removal process. Titanium matrix composites are generally outgassed in the hot press with 10 to 20 atmospheres of pressure.

Hot Press Consolidation

Consolidation is the most critical step in the process and also the most limiting. Table 2 gives the parameters for hot pressing.

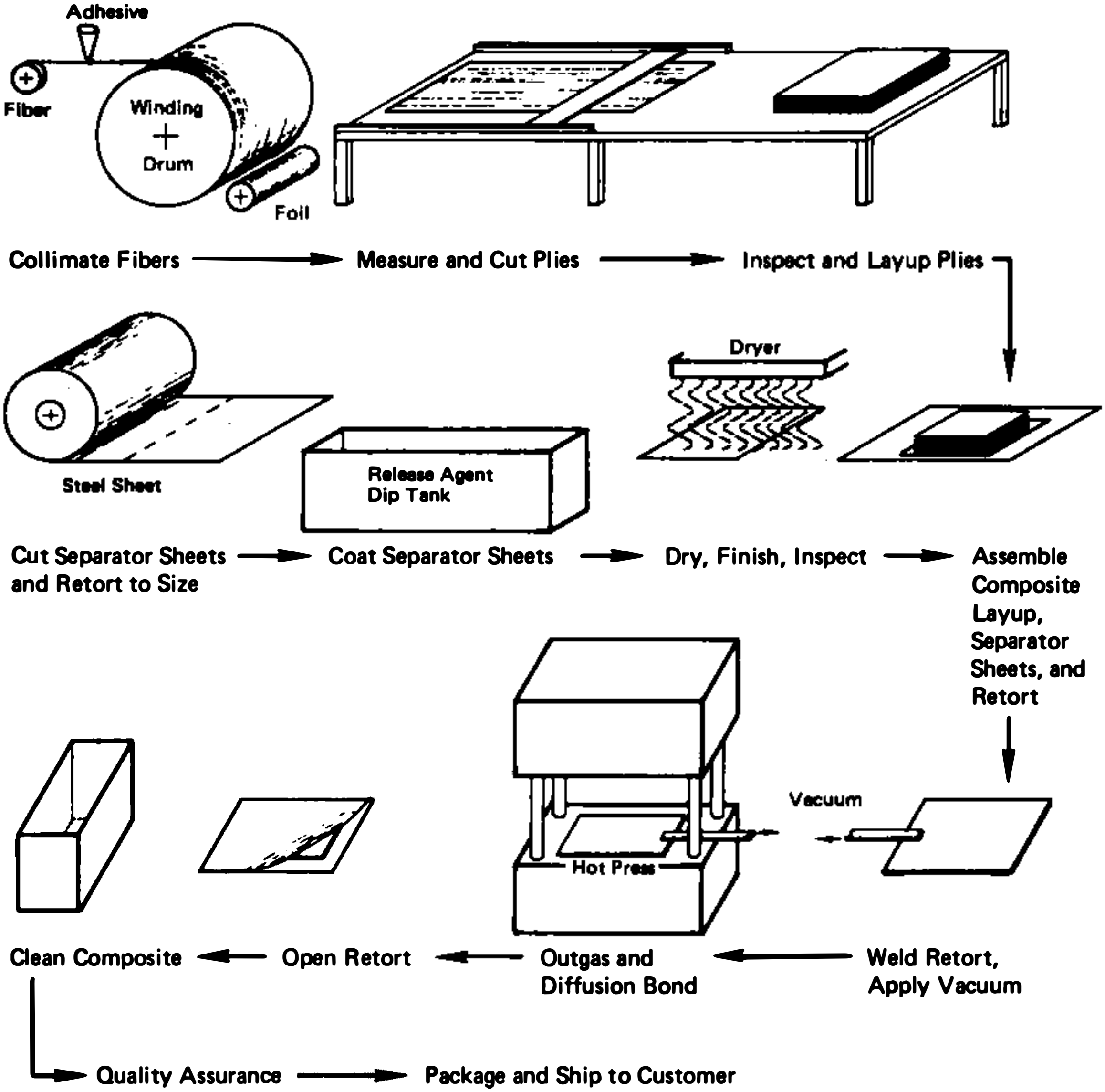


FIGURE 9 Process flow chart for diffusion-bonded B/Al composite (courtesy of Amercom, Inc.)

TABLE 2 Parameters for Hot Pressing

System	Temperature °F (°C)	Time at Temperature	Minimum Pressure ksi (MPa)	Step Pressing	Comments
B/Al	985 (530)	30 minutes	5 (35)	Yes	Filament degrades with long exposures
BorSiC/Al	985 (530) to solidus	30 minutes	5 (35)	Yes	Filament resists degradation
B_4C/B	985 (530) to solidus	30 minutes	5 (35)	Yes	Filament resists degradation
SiC/Al (SCS-2)	985 (530) to solidus	30 minutes	5 (35)	Yes	Filament resists degradation
B_4C/Ti-6-4	1700 (925)*	30 minutes (maximum)	6 (41)	No	Filament degrades
SCS-6*/Ti-6-4	1700 (925)*	30 minutes (maximum)	6 (41)	No	Filament resists degradation
BorSiC/Ti-6-4	1700 (925)*	30 minutes (maximum)	6 (41)	No	Filament degrades

*Lower temperatures, longer times, and lower pressures are possible at the expense of composite strength. Other conditions may be used if stiffness alone is required.

Secondary Fabrication

The secondary fabrication steps are as numerous as the specific applications. The typical hot press flat panel can be produced by diffusion bonding. The panel is a good form for testing, but in general few applications are in the form of simple panels. Thus, secondary fabrication is required.

One type of secondary fabrication operation is shown in Figure 10. Here, a panel is fabricated and is subsequently formed into the desired shape by lower pressures using heated matched die tooling. This process is termed "creep forming."

A second example of secondary fabrication is shown for the space shuttle tubes in Figure 11. Monolayer produced by step-press diffusion bonding is rolled about an internal bladder mandrel. The wrap is slipped into a cylindrical female tool, evacuated and sealed, and subjected to HIP consolidation. End attachments are consolidated to the tube in situ.

Hot Molding

Hot molding is defined as composite consolidation at temperatures above the solidus of the matrix alloy but below the liquidus. Since there is liquid phase present, consolidation takes place at low pressures compared to the vacuum hot press diffusion bonding described earlier. Thus, the production capacity of the hot press is greatly extended, since lower pressures can be translated into larger parts for a given press capacity. Alternatively, consolidation can take place in an autoclave.

Hot molding cannot be considered to have the state-of-the-art status of diffusion bonding. However, recent National Aeronautics and Space Administration and Air Force laboratory programs are rapidly advancing the process to the point where simple "Z" and curved panels are being reliably produced.

There are two basic requirements for hot molding: the filament must not be degraded by the hot molding process, and a liquid and solid phase must be simultaneously present.

The first requirement is met to various degrees by three microfilaments--SCS-Z (silicon carbide) and B_4C-B (boron carbide coated boron), produced by AVCO, and BorSiC^{TM} SiC-coated boron produced by CTI. In addition to these monofilaments, some graphite-aluminum wires could be fabricated by hot molding techniques if fiber degradation can be controlled or tolerated for a specific application.

The requirement of the presence of a liquid phase can be met by either choosing a matrix alloy with a reasonable range between the liquidus and solidus or by choosing a bimetallic system. Alloy 6061 with an 1100 to 1200°F solidus/liquidus range has been most often utilized. The bimetallic 6061/4343 system has also been examined but to a lesser extent.

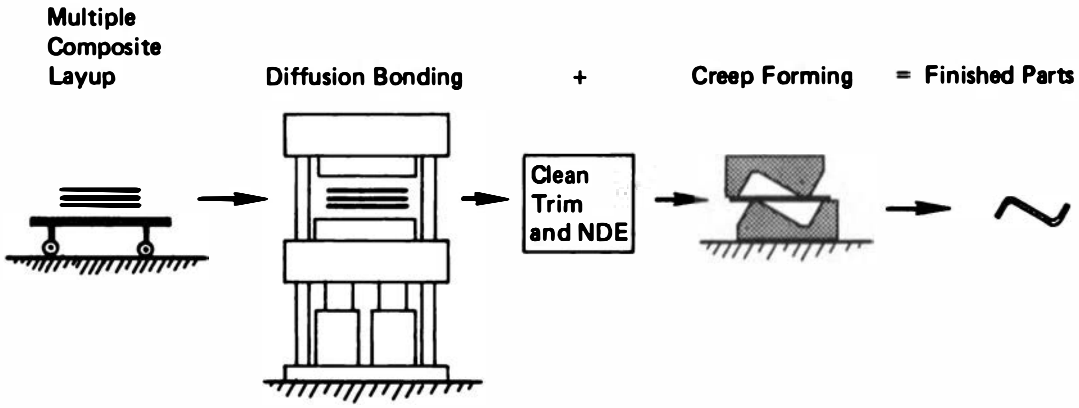


FIGURE 10 Schematic representation of press diffusion bonding and creep forming process (courtesy of Amercom, Inc.).

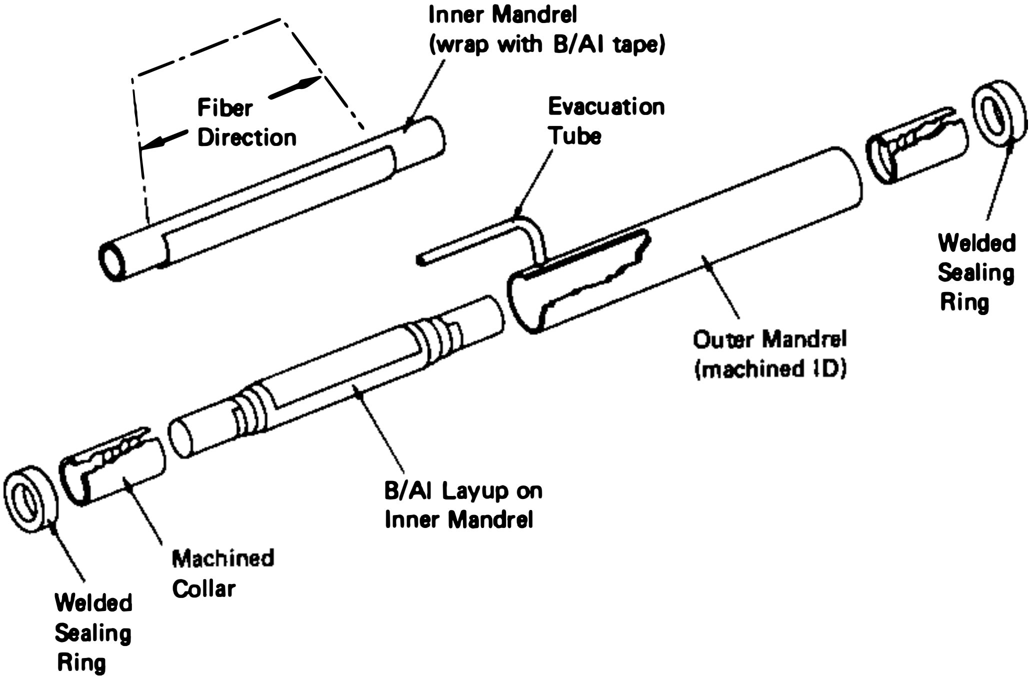


FIGURE 11 Boron/aluminum tube assembly fabrication (Source: General Dynamics Conver Division).

Drum Wrapping

Drum wrapping (Figure 12) is identical to the step described for diffusion bonding except the fugitive binder is not applied. Typically, if the matrix is to be A6061, a foil of that alloy is used to line the drum prior to level winding of the filament onto the drum. The foil will later become a part of the preform.

Plasma Spraying

Plasma spraying (Figure 13) is a substitute for the binder additions step in diffusion bonding. Plasma spraying of the desired alloy simultaneously fixes the filaments into position and adds the remainder of the matrix material to make up the desired matrix volume fraction. In this case, the volume fraction is continuously variable by adjusting plasma spray parameters. Proper control of cover-gas is required to prevent the entrapment of Al_2O_3 overspray into the monolayer.

Hot Mold Consolidation

The essence of hot molding is pressurizing above the solidus of the matrix. With proper attention to vacuum integrity in the tool holding box, and a clean plasma spray system, a composite part can be consolidated into structural shapes such as hot stringers and "Z" sections. Ogive (pointed arch) sections--both regular and segment sections of rotations such as nose cone shapes--can be produced with ease. There are two major variations of

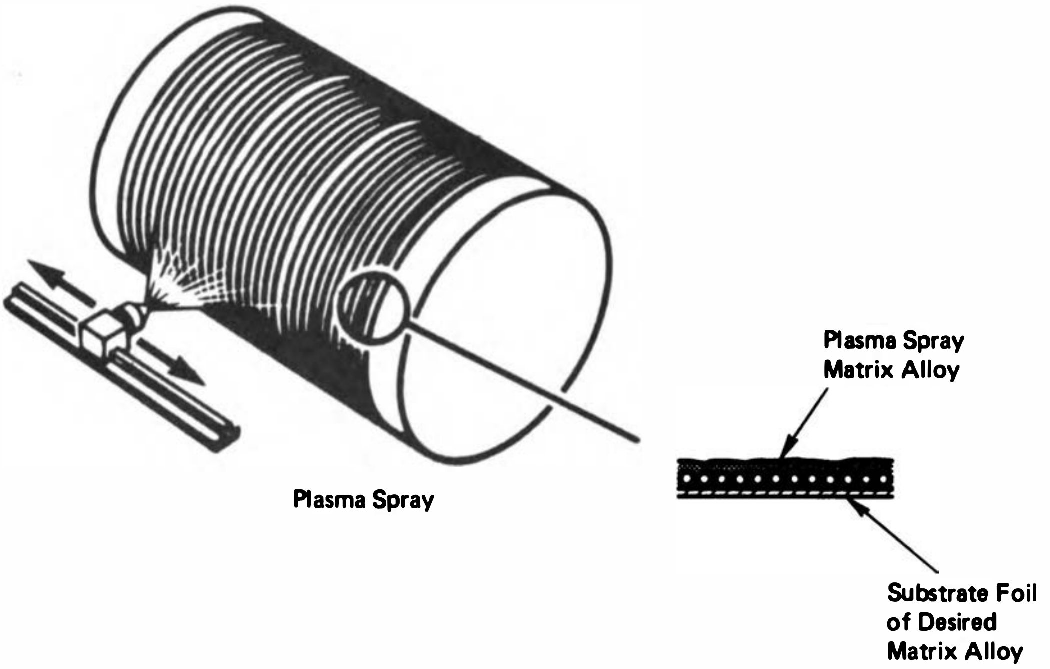


FIGURE 12 Drum wrapping on aluminum foil (courtesy of AVCO Corporation).

FIGURE 13 MMC fabrication by plasma spraying (courtesy of AVCO Corporation).

hot molding: evacuated tool--regular shapes, panels, and ogive gore segments (Figure 14), and isolated panel, external tool--good for same parts, best for broad curved panels (Figure 15).

In the first (evacuated heated tool) method, the pressure acts through a single bladder onto an evacuated heated tool as shown in Figure 14. This geometry is best suited for stringers and simple curved panels.

The second method is merely an extension of the well-established vacuum hot-press, bagging technology. However, here the upper and lower bladder are preformed before loading with the plasma-sprayed preform and are seam-welded and vacuum-ported in the conventional manner. The heated matching cast ceramic tool conforms the part to the compound curvature by simple spring-loaded clamps. Consolidation is performed during the hot molding operation by the action of autoclave pressure acting through the upper and lower bladder as the preform is uniformly heated above the alloy solidus.

The following systems have been used in applications of hot molding: SCS-Z/Al, B_4C-B/Al, and BorSiC/Al. Most of the development has been performed on the SCS-Z/6061 system. The SCS-Z filament has been shown to prevent degradation even after prolonged exposure (up to 4 hours) at 1250°F in molten A6061. Some candidate components for this process are stringers (zees, hats, and ogives) and gores (bay covers).

Flaws can be of four types: disbonds, splices, spacing, and crossed filaments.

Disbonds result from contamination of the preform, improper outgassing of binder (resulting in blisters), inadequate evacuation, improper platen alignment, dished platens, or improper fiber alignment. Of these, dished (crushed) platens is the most common.

Splices result from filament breaks during rewinding or reactor-run ends. As a result, there can be spacing errors or local contamination during outgassing. In general, splices are not a serious defect.

Spacing errors are caused by vibration during drum wrapping, filament "swimming" during outgassing, insufficient wrapping tension, step pressing, or hard contaminants on foil. The problem is more severe with hard foils such as titanium.

Crossed filaments result from improper wrapping tension, poor repair techniques, or improper restraint during outgassing.

CONTINUOUS MULTIFILAMENT YARN REINFORCEMENT

Precursor Wire

Graphite-aluminum (Gr/Al) precursor wire is produced by continuously infiltrating graphite fibers in a liquid metal infiltration unit. The fiber sizing is removed prior to entering the chemical vapor deposition (CVD) unit. In this chamber titanium tetrachloride and boron trichloride are

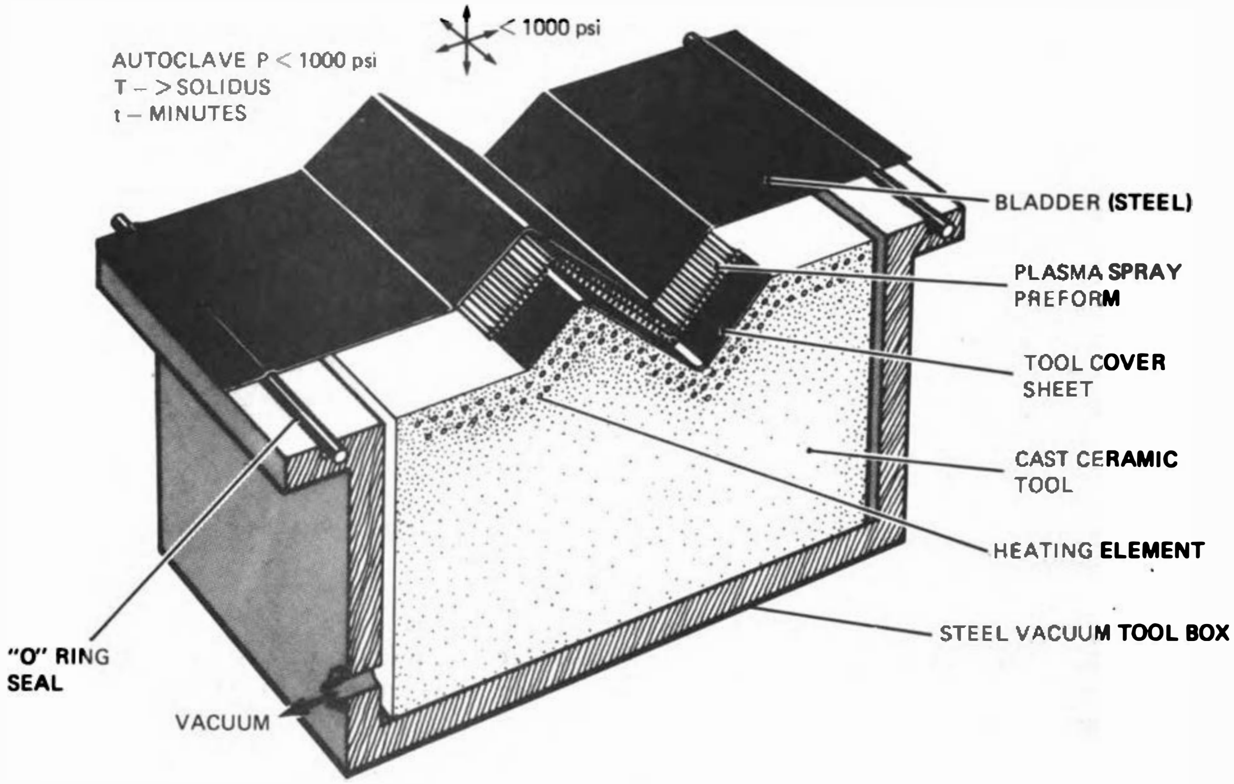


FIGURE 14 Evacuated tool hot molding (courtesy of AVCO Corporation).

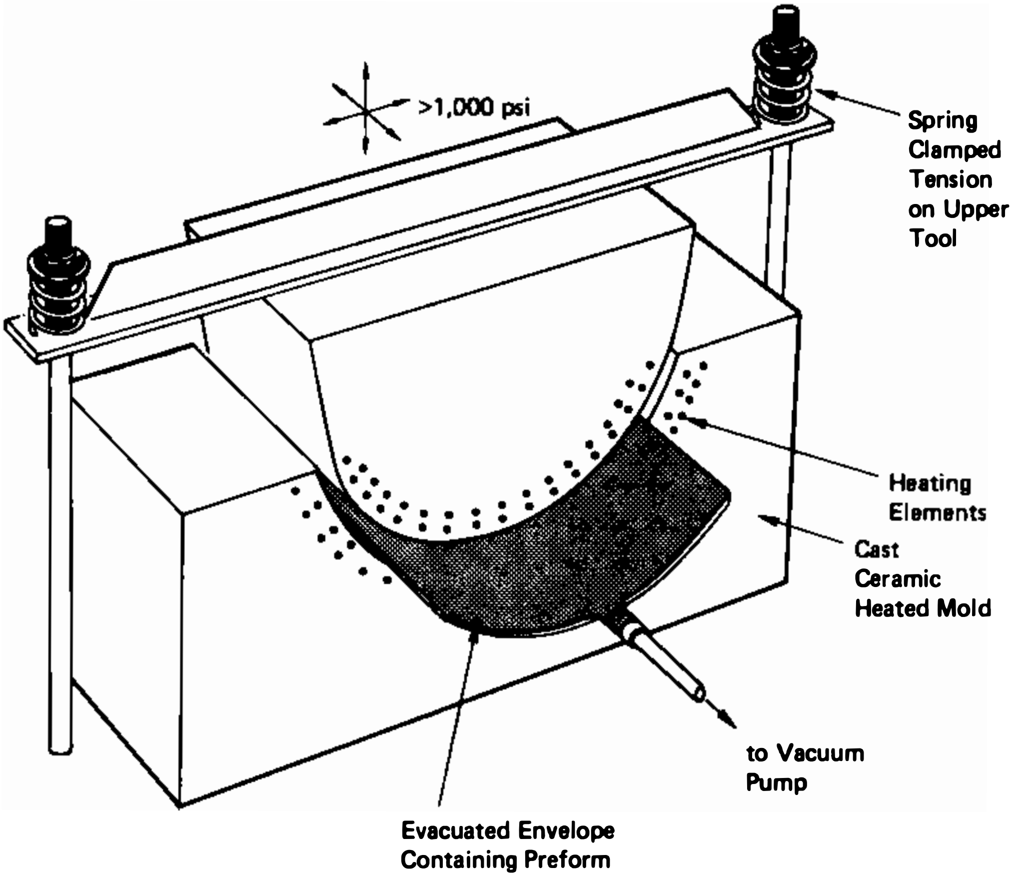


FIGURE 15 External heated tool hot molding (courtesy of AVCO Corporation).

reacted over a zinc boat to form a complex coating on the graphite surface. This allows the aluminum to wet the fiber surface. (Aluminum normally does not wet graphite.) The wire is then formed by passing the coated graphite fibers through molten aluminum and cooling. Figure 16 is a schematic diagram of this process. Graphite-magnesium and graphite-copper wires are manufactured in a similar fashion.

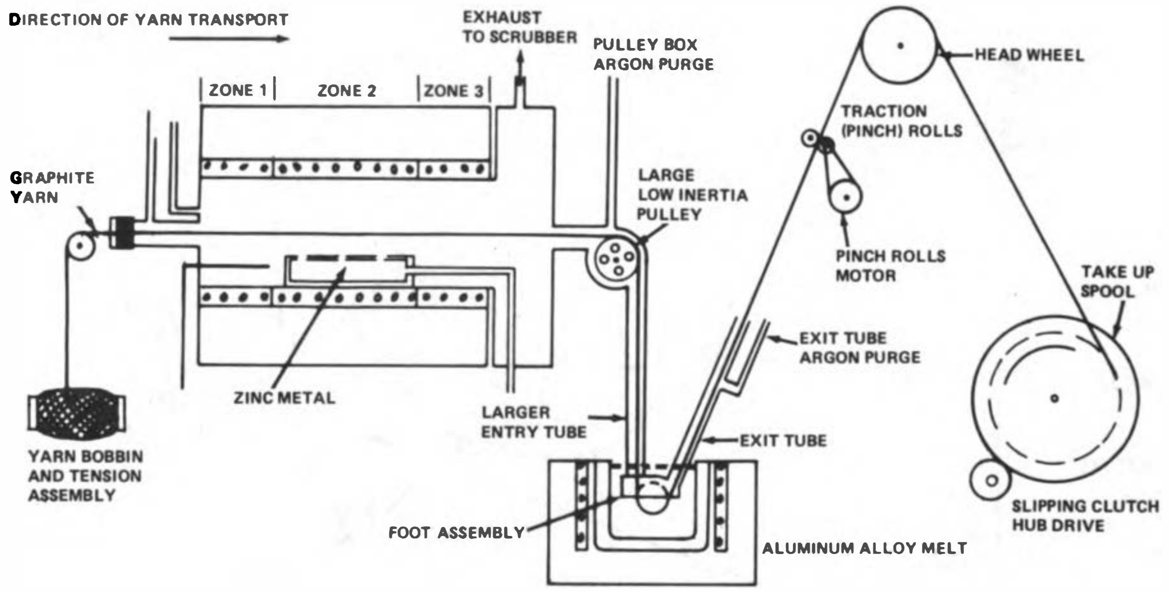


FIGURE 16 Liquid metal infiltration unit (courtesy of Material Concepts Inc.).

Defects that can occur during this manufacturing process are noninfiltrated areas, both surface and internal (Figure 17), and "fuzz" generated bridging, "fuzzballs," and melt slag balls (Figure 18). In addition, irregular wire shapes, although not a manufacturing defect per se, can lead to defects in the secondary fabrication process. Many surface defects are developed in part from collection of staple fibers on the melt surface (Figure 19) and have been reduced by the introduction of a liquid metal pump infiltration technique (Figure 20).

The major fabrication procedures for making the wire into usable end item shapes are diffusion bonding and pultrusion. In the diffusion bonding procedure, the wires are laid side by side and then foils are placed on both

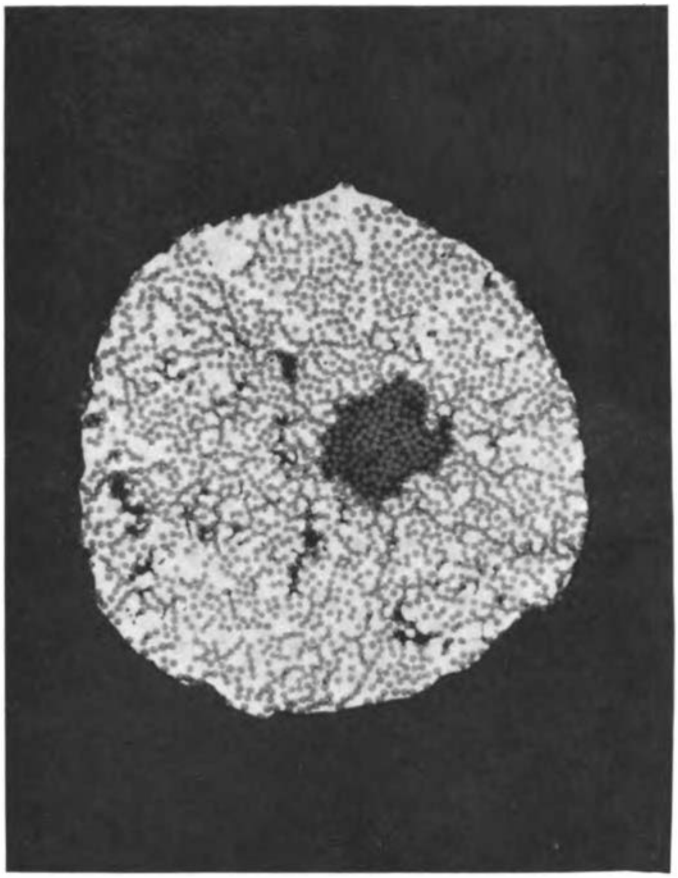


FIGURE 17 Photomicrograph cross section of graphite-aluminum wire showing noninfiltrated area (courtesy of Naval Surface Weapons Center).

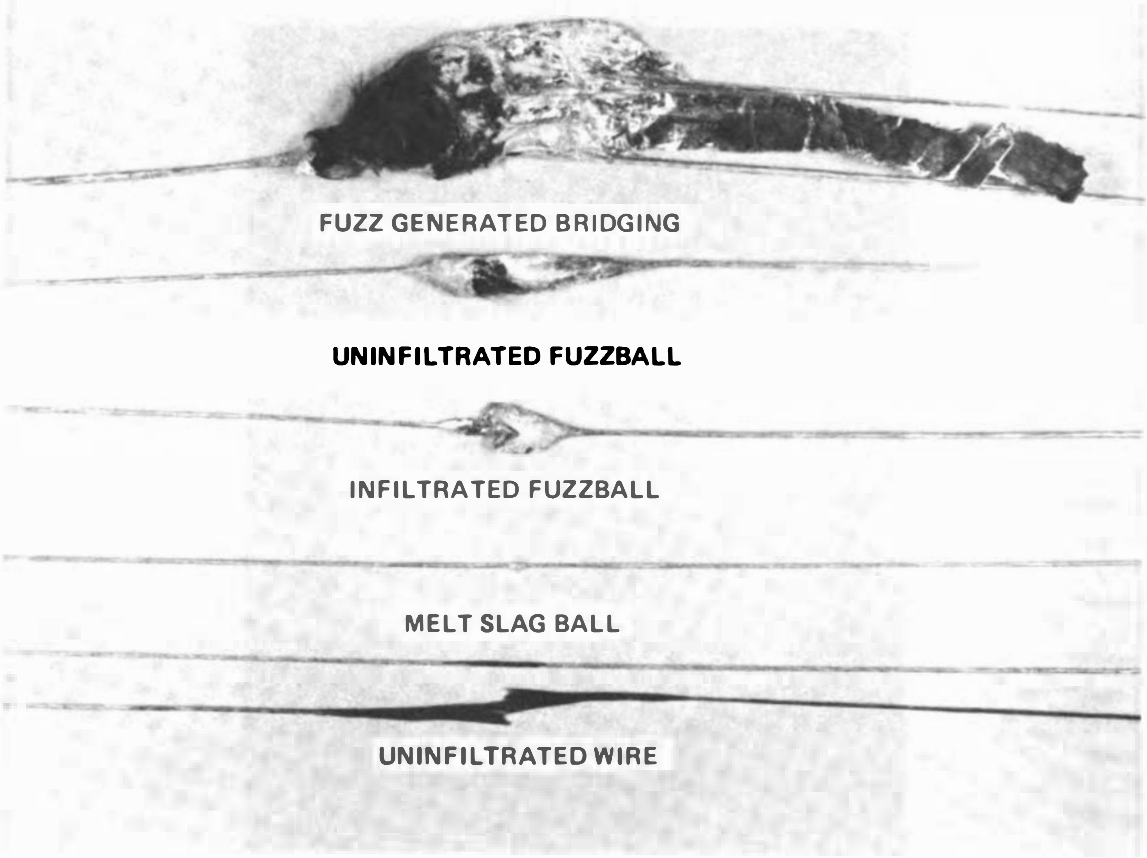


FIGURE 18 Surface defects found on graphite-aluminum wires (courtesy of Naval Surface Weapons Center).

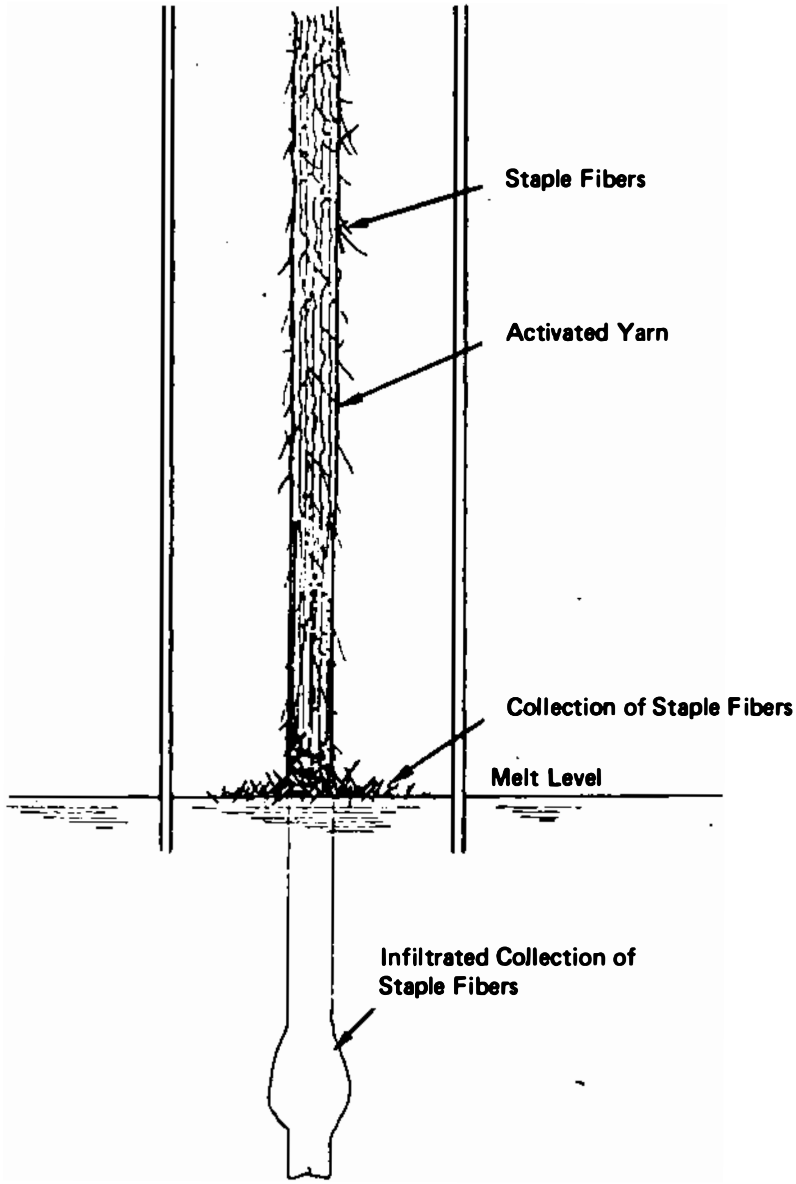


FIGURE 19 The formation of "fuzzballs" (courtesy of Material Concepts, Inc.).

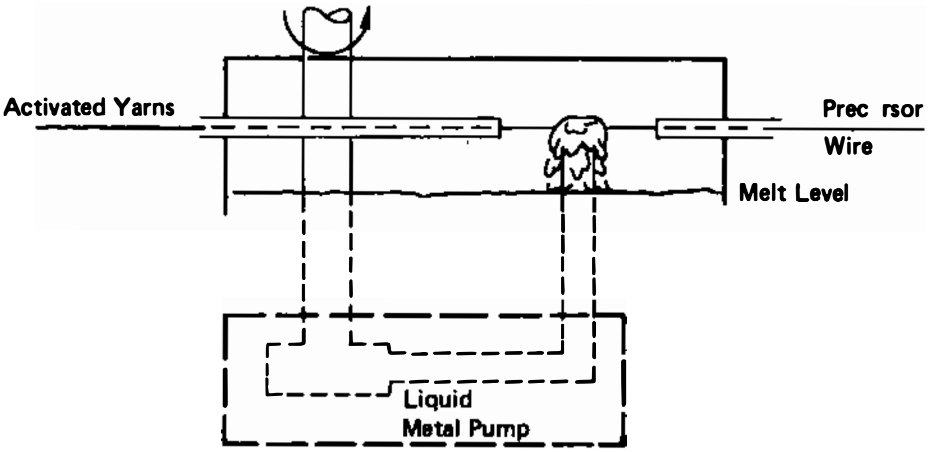


FIGURE 20 Liquid metal pump setup (courtesy of Material Concepts, Inc.).

sides of the wires. This configuration is placed in a stainless steel bag that is evacuated and the entire assembly is pressed at elevated temperature. Shaped configurations can be formed by hot pressing between appropriately shaped male and female combinations. Properly consolidated material contains a void-free structure that is metallurgically bonded at all wire-wire and wire-foil interfaces. Use of inadequate consolidation procedures can result in defects--among them porosity, internal cracking, wire misalignment, wire fracture, aluminum-rich zones, delamination of encapsulant foil or cladding, and internal disbonds. It should be noted that any flaws present in the initial precursor wire are not removed by the secondary consolidation step.

Pultrusion (i.e., roll-drawing) is a fabrication process that loads the uniaxial reinforcement in axial tension during secondary processing. During consolidation of symmetrical configurations at elevated temperatures, a homogeneous, hydrostatic deformation condition is approached as each composite volume element passes through a die. High compressive surface stresses balance interior tensile stresses, resulting in a state of nearly homogeneous deformation during bonding of the composite wire preforms. A schematic of a typical pultrusion is shown in Figure 21.

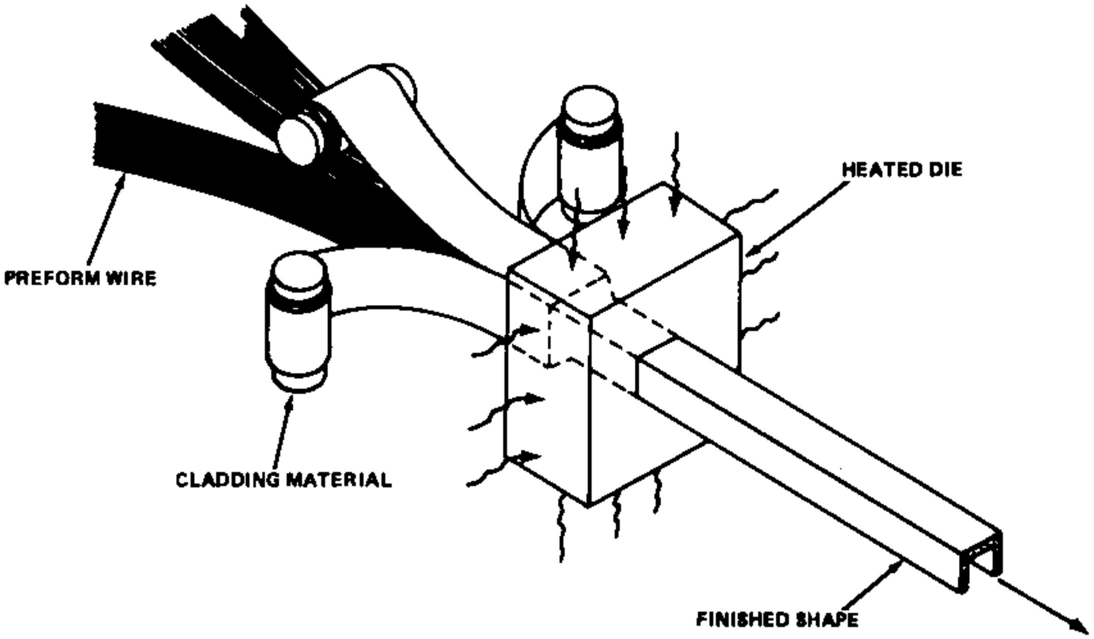


FIGURE 21 Typical pultrusion setup (courtesy of Material Concepts, Inc.).

Certain problems may be encountered by the Gr/Al user after the diffusion bonding step. Electrical resistance spot welds have been found to be porous in many instances, and drilling of fastener holes can generate a fracture that runs parallel to an individual precursor wire. Use of the cross-ply (0° to 90° to 0°) stacking arrangement in a part can result in microcracking occurring normal to the fiber direction of each ply. This failure phenomenon owes its source to differential thermal shrinkage between the axial and transverse directions of the Gr/Al lamina. Gr/Al is not amenable to being shaped by deformation processing, which involves large amounts of matrix deformation. Mechanical working of this composite tends to degrade the fiber-matrix interface and reduce material strength. This type of defect is subtle in that, on a macroscale, the material appears to be in proper condition. Figure 22 shows some of the defects that have been observed in Gr/Al panels.

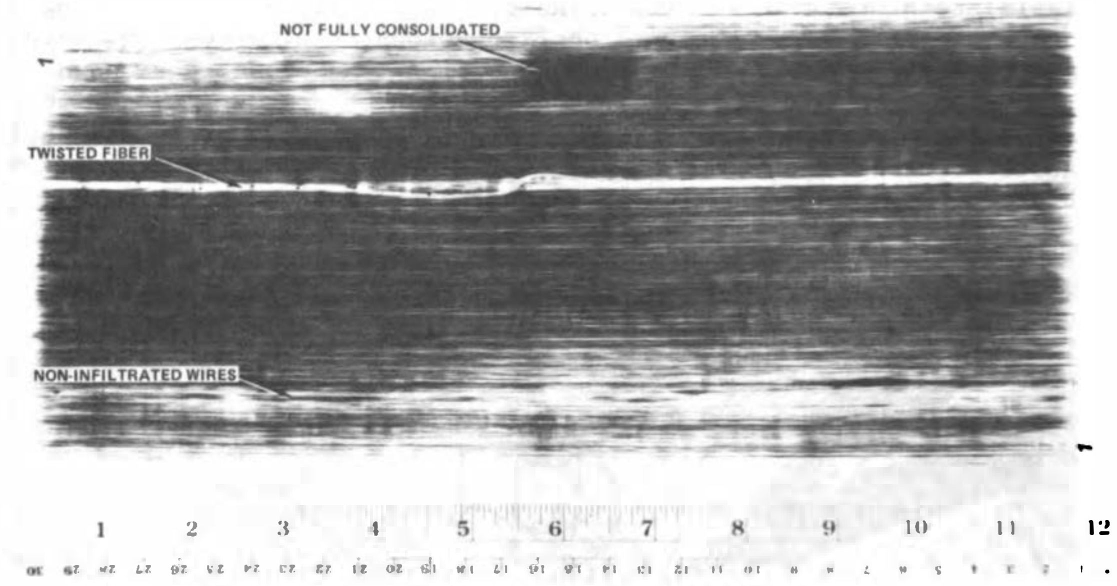


FIGURE 22 Some typical defects in a graphite-aluminum panel (courtesy of Naval Surface Weapons Center).

Preform-Vacuum Infiltration

The du Pont fiber FP/MMC (Champion 1978) is prepared using a preform technique. A tape containing a fugitive binder is first prepared. The preform is then produced by lay-up onto a mandrel, ensuring that the proper fiber orientation and shape are achieved and that the proper fiber volume loading is obtained. This lay-up is then placed into the mold, which has had a washout applied to the internal surfaces. The binder is removed from the FP preform and the evacuated system is infiltrated with the molten matrix metal.

Major types of defects that occur during the FP/matrix fabrication are formation of matrix rich areas, poor infiltration, and excessive fiber-matrix reaction. The matrix-rich and void regions may result from improper preform fabrication. Photomicrographs of these defects (plus a homogeneous region) are shown in Figure 23. The poor infiltration can result from incorrect processing time, temperature, or lithium concentration in the alloy (Figure 24). Excessive fiber-matrix reaction, resulting from elevated casting temperature, infiltration time, or lithium concentration, will result in fiber degradation and splitting and reduced mechanical properties. Figure 25 shows examples of both void areas and fiber-matrix reaction zones.

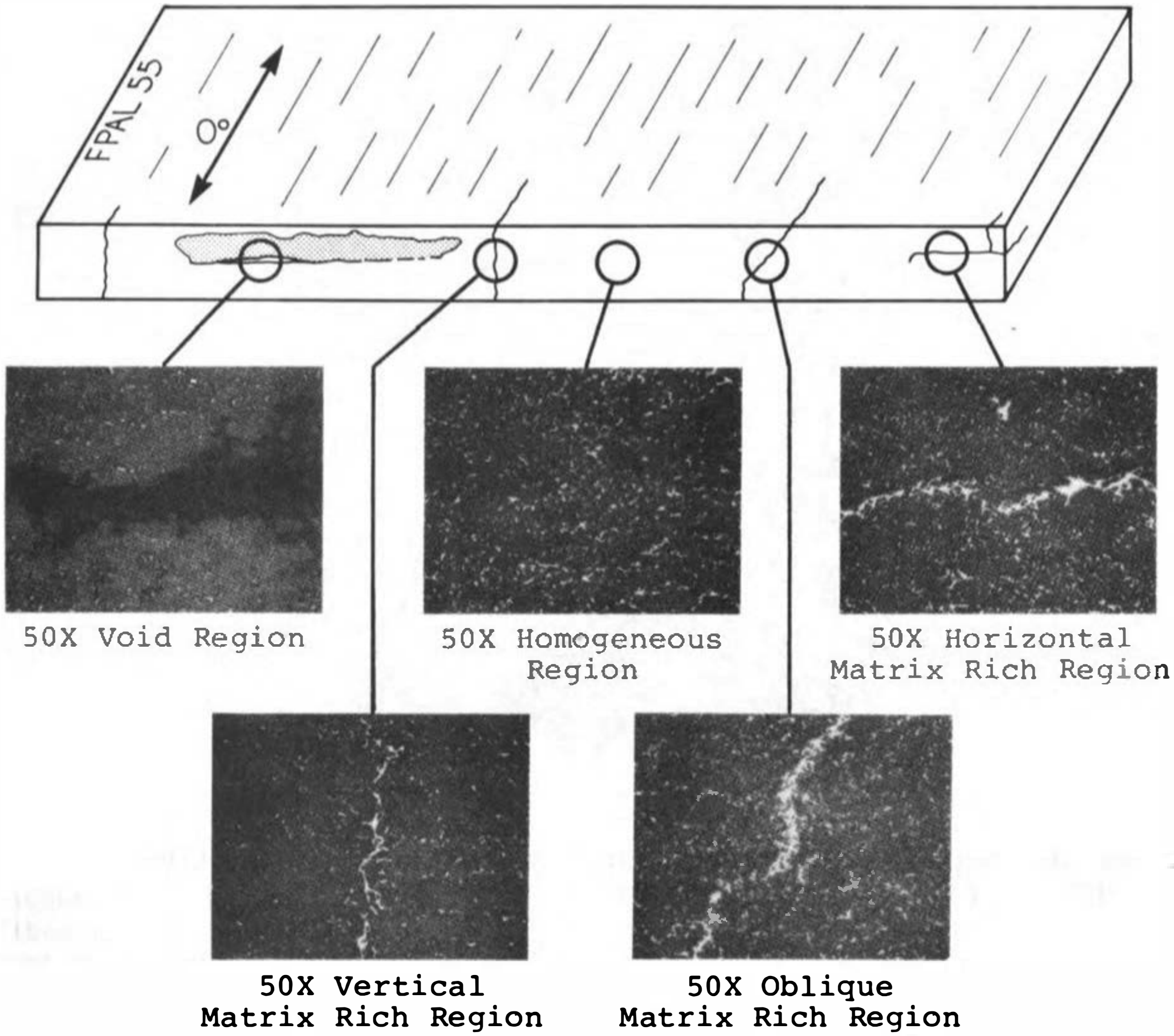


FIGURE 23 Photomicrographs of matrix-rich and void regions in 55 percent volume fraction FP aluminum (courtesy of E. I. du Pont de Nemours and Company).

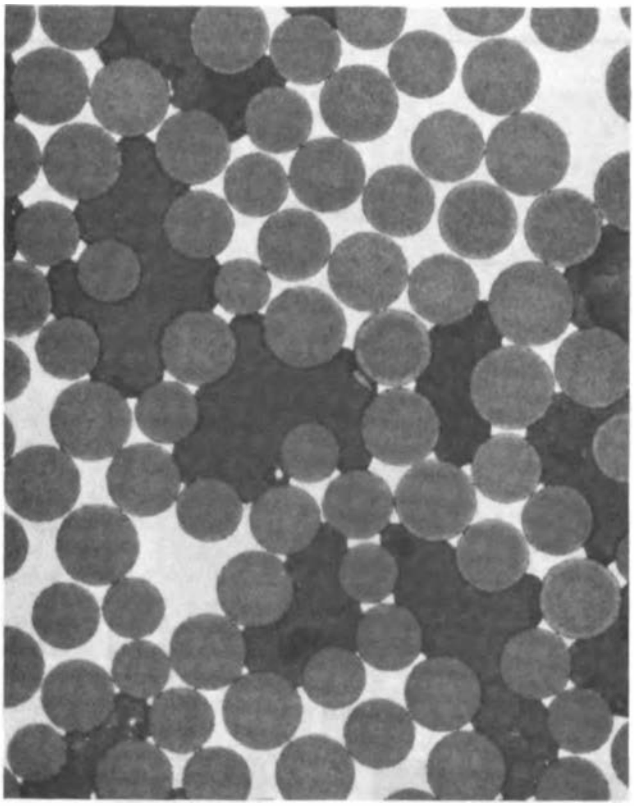


FIGURE 24 Photomicrograph showing areas of poor infiltration (500X) (courtesy of E. I. du Pont de Nemours and Company).

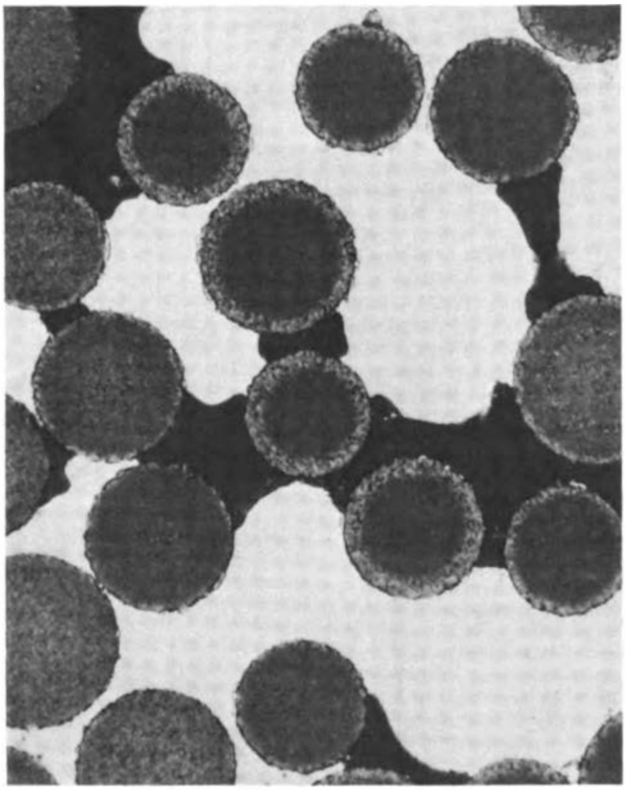


FIGURE 25 Photomicrograph showing reaction zones around fibers due to fiber-matrix reaction; voids are also present (1000X) (courtesy of E. I. du Pont de Nemours and Company).

Chapter 4

FAILURE MECHANISMS

A structure subjected to mechanical loads and temperature changes behaves in a manner dictated by the property of its constituent elements. The scientific discipline dealing with these subjects is mechanics.

Metal matrix composites are complex, heterogeneous materials, consisting of elastic-plastic matrices reinforced by continuous and discontinuous fibers, whiskers, and particles. Reinforcements are usually brittle ceramic materials that often display no ductility. The branch of mechanics that relates macroscopic material behavior to the properties of the constituents and their geometric arrangement in the composite is called micromechanics. Evaluation of the effects of defects on composite behavior is generally based on micromechanical or semi-empirical models, or empirical data. Good models are extremely valuable, as they minimize the amount of expensive testing required.

To date, micromechanical analyses have concentrated on composites with elastic matrices and reinforcements. However, because plasticity effects are important in metal matrix composites, there are large gaps in our understanding of these materials (Zweben 1983). This section reviews what is known about the micromechanics of metal matrix composites. Stress-strain behavior, static strength, and fatigue characteristics are covered.

STRESS-STRAIN BEHAVIOR

The contribution of metal matrices to composite stiffness, even in the axial direction, can be significant, and matrix plasticity effects can have an appreciable influence on composite behavior.

Composite plastic load-deformation behavior is far more difficult to describe than for the elastic or even viscoelastic cases. In these last two instances, it is possible to use effective composite properties to obtain relations between average stresses and strains and their time derivatives. However, to describe plastic behavior, it is necessary to define the complete internal state of stress for every value of applied load. This requires specification of a geometric model and is extremely complex, even for simple loading conditions. The problem has been approached both analytically and by use of finite element models (Hill 1964; Mulhearn et al. 1967; Dvorak and Rao 1976a; Adams 1970; Foye 1973).

The complexity of the subject precludes a detailed discussion of plastic load-deformation behavior. However, micromechanical analyses have provided important insights into the general characteristics of composites with plastic constituents, and these will be examined in this section. The discussion is based primarily on the work of Drucker (1975) and Dvorak and Rao (1976a, 1976b).

The elastic constants of fiber and matrix usually differ, so the internal stress distribution is not homogeneous, even under hydrostatic loading. Unexpected results follow from this; e.g., a composite with elastic fibers in an elastic perfectly plastic matrix shows an initial stress-strain curve with work hardening caused by the formation of plastic zones which spread as the load is increased. The application of hydrostatic stress produces irreversible volume changes caused by yielding of the matrix, although the matrix is plastically incompressible.

Dvorak and Rao (1976b) showed that plasticity effects often are important when composites whose constituents have different coefficients of thermal expansion undergo significant temperature change.

A simple model for the behavior under axial load of a composite with elastic fibers and an elastic, perfectly plastic matrix presented by Spencer (1972) illustrates some of the effects of plasticity on composite behavior. Figure 26 shows the stress-strain behavior of the composite; the fibers, which have an elastic modulus E_f; and the matrix, which has an elastic modulus E_m, a tensile yield stress Y_m, and a compressive yield stress $-Y_m$. Assuming the composite is originally stress-free, the initial modulus is approximately $cE_f + (1 - c)E_m$ where c is the fiber volume fraction. The matrix yields when the applied stress is $[cE_f + (1 - c) E_m] Y_m/E_m$ (point A), and the effective composite modulus drops to cE_f. The slope of the unloading curve, BC, equals the initial elastic slope. At point C, the matrix stress reaches $-Y_m$ and it yields in compression, whereupon the effective composite modulus again drops to cE_f. At point D, where the applied stress is zero, the matrix is under a state of residual compressive stress, $-Y_m$, the fibers are in tension, and there is a macroscopic residual deformation. Subsequent application of tensile stress unloads the matrix, and it behaves elastically, so that the slope of the composite stress-strain curve is, again, $cE_f + (1 - c) E_m$. At point E, the matrix yields in tension. The cycle EBCD can then be repeated indefinitely.

This simple model does not display the apparent work hardening predicted by more detailed analyses (Dvorak and Rao 1976a, 1976b). Composite behavior under shear and transverse extensional loadings is more complex and is not easily represented by simple models like the one presented here (Adams 1970, Foye 1973).

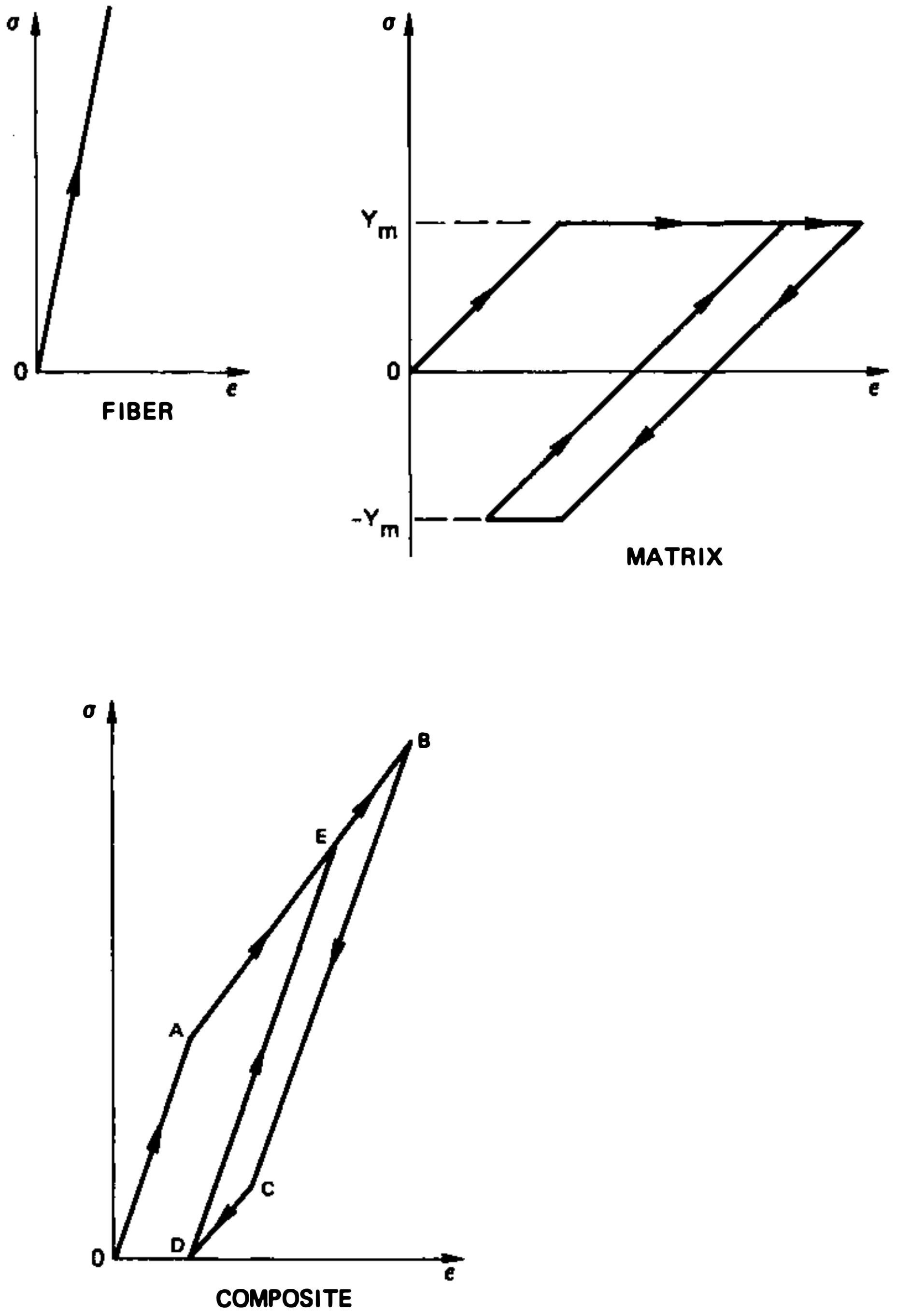


FIGURE 26 Stress-strain curves for elastic fibers, elastic perfectly plastic matrix, and composite.

The influence of thermal history is another extremely important factor affecting composite stress-strain behavior. Metal matrix composites are fabricated at very high temperatures, resulting in residual stresses intense enough to cause yielding of the matrix (Dvorak and Rao 1976b). Furthermore, heat treatment determines the magnitude of the matrix yield stress, which affects composite constitutive behavior as well as strength.

AXIAL TENSILE STRENGTH

This section treats the axial tensile strength of metal matrix composites having continuous, parallel fibers, which are assumed to be brittle ceramic materials, such as boron, carbon, and alumina.

Fibers do not have unique tensile strengths. These brittle materials are flaw-sensitive, and their strengths display considerable scatter when tested at a fixed gauge length. Furthermore, mean strengths decrease with increasing gauge length (Zweben 1977). Because of the nature of fiber strength, composite tensile failure is a complex process associated with random fiber breaks scattered throughout the material.

There has been relatively little study of the failure mechanisms in most metal matrix systems, except for boron-aluminum. There is evidence that some boron-aluminum systems fail catastrophically, with a minimum number of scattered breaks, while in others, numerous random fractures are observed (Herring 1972, Wright and Wills 1974). The reasons for the different failure modes have not been definitively established, although fiber-matrix interfaced bond strength appears to be a major factor.

A number of analytical models for composite tensile strength have been proposed, but correlation with experimental data, especially for metal matrix composites, has been meager (Argon 1974, Zweben and Rosen 1970, Phoenix 1983).

A major concern in processing metal matrix composites is the possibility of fiber-matrix interaction during processing, with resultant fiber degradation. The formation of a reaction layer on fiber surfaces might have little effect on composite modulus but could cause a significant reduction in composite tensile strength.

Because matrix stiffness is significant compared to fiber stiffness for most metal matrix systems, matrix temper and residual stress state can also affect composite tensile strength.

Reinforcing fibers generally carry a major share of the load, and thus any damage to them, such as that resulting from impact, can cause significant strength reduction (Awerbuch and Hahn 1976). The problem of predicting fracture of damaged composites is controversial at present, and use of conventional fracture mechanics techniques is not universally accepted (Zweben 1973).

AXIAL COMPRESSIVE STRENGTH

The axial compressive strength of fiber-reinforced materials is strongly influenced by the microstructural geometry of the material. For aligned fiber geometry, the material strength is determined by instability of the fibers supported by the matrix phase. It should not be surprising to learn that, since the buckling load of the fibers is influenced by the degree and tenacity of support by the matrix phase, the matrix properties, as well as fiber matrix bond integrity, play important roles in determining axial compressive strength of aligned fiber composites. Thus, defects that can be expected to influence axial compressive strength of these materials include fiber alignment or collimation, fiber-matrix bond integrity, and matrix in situ stiffness properties. For multiaxial laminates of aligned fiber composites, interlaminar fracture followed by laminae instability is another mode of compressive failure. Here individual laminae or groups of lamina at the surface become unstable when they lose the support of the adjacent material through interlaminar fracture. Hence, interlaminar defects are significant in determining the axial compressive strengths of multiaxial laminates.

The axial compressive strength of discontinuous fiber composites may not be determined by instability of the fibrous phase; instead, failure may result from a complex process of matrix yield and crack propagation. For discontinuous fiber composites, uniformity and integrity of microstructural geometry, as well as fiber matrix adhesion, strongly influence strength. Thus defects such as matrix voids and variations in fiber or particle spacing are important in determining compressive strength. Furthermore, orientation state of ellipsoidal particles and short fibers will strongly influence compressive properties.

TRANSVERSE STRENGTH PROPERTIES

The transverse strength of aligned fiber composite materials is determined both by the quality of the bond between fiber and matrix as well as the properties of the in situ matrix. In cases of highly anisotropic fibers where the transverse strength of the fiber is less than that of the bond, fiber failure may contribute to transverse composite failure. Since the presence of voids acts to limit the surface area for adhesion, voids may strongly reduce transverse tensile strength. On the other hand, fiber misalignment can be expected to enhance transverse tensile strength when compared to that for the perfectly aligned composite. Fiber spacing variation may act to reduce transverse tensile strength when the changes in spacing results in increases in fiber volume fraction locally. This is because stress concentrations in the matrix phase caused by the fiber are increased when fiber volume fraction is increased.

The transverse tensile strength of particulate and discontinuous fiber composites, like the axial tensile strength, is determined by a combined matrix and fiber-matrix interface failure. Thus the geometry of the microstructure can be expected to strongly influence strength. A random orientation distribution of reinforcement will exhibit greater transverse tensile strength than that of a greater degree of fiber collimation.

FATIGUE MECHANISMS

The elastic-plastic response of metal matrix composites to cyclic loads has been the subject of numerous papers (Dvorak and Johnson 1980 and 1981; Johnson 1980). Results of Dvorak and Johnson's theoretical and experimental studies of fatigue damage mechanisms in unidirectional and laminated boron-aluminum show three types of response to cyclic loading.

First, at relatively low load amplitudes, there is no evidence of damage that can be detected by stiffness measurements or by microscopic examination. This is called the shakedown stress range, within which the composite, in particular the matrix, resumes an elastic deformation mode after a certain number of plastic strain cycles.

Second, when the overall cyclic stress range is such that the composite does not shake down, the aluminum matrix undergoes cyclic plastic straining in one or more layers of the laminate. As a result, low cycle fatigue damage develops in the matrix, first in the form of families of parallel long cracks that propagate in the direction of the fibers in off-axis layers of the laminate. These crack families are usually confined to their particular plies by the fiber layers in adjacent plies. At higher applied stress ranges, after many loading cycles, such crack families are observed also in the matrix of the zero-degree plies, where their direction is perpendicular to that of the fiber and of the applied load. This internal crack damage causes the reduction of the elastic stiffness of the laminate. The loss of stiffness may be quite substantial, sometimes equal to 50 percent of the original magnitude, especially in laminates with relatively many off-axis layers. In addition to the loss of stiffness, damaged laminates also suffer a reduction of residual static strength.

The fatigue damage process does not necessarily continue indefinitely, nor does it need to cause early failure. As long as the maximum applied load does not exceed the endurance limit for a given stress range, the damage process becomes arrested after 0.5 to 1.0 X 10^6 cycles of loading. Quantitative theoretical understanding of the evaluation of the damage process is still incomplete. However, experimental evidence suggests the following sequence of events. The initial families of long cracks form in the weakest off-axis layers, or in those that are subjected to relatively high transverse stresses that cannot be supported by the matrix. Local cracking in these layers reduces their stiffness and, consequently, the magnitudes of local stress that the layers need to support. This is the first step in a gradually evolving process of load transfer from the cracked, compliant plies of the laminate to the stiffer layers. As the weakest or highly stressed parts of the microstructure fail, their share of the load is transferred to the undamaged material. When the applied load increases, or is continued in a cyclic fashion, this process proceeds to operate, and it causes damage accumulation. The damage sequence can be arrested if, at a certain state of damage accumulation, the combined effects of internal stress redistribution and external loading cannot cause further cracking in the composite material. This final damage state, if it exists, is referred to as a "saturation damage state."

It appears that the saturation state is reached when local stresses in the cracked off-axis layers have been reduced to such levels that no further cracking may take place in these layers. Much of the total applied load is then transferred to the zero-degree layers. Two possible outcomes may follow. If the zero-degree layers and the surviving parts of the off-axis layers can support the applied load without further damage, the composite reaches the saturation damage state and suffers only the attendant loss of stiffness and strength, but no failure.

The third type of response is when the stresses are too large for the saturation state to develop; then the damage process continues to the point where the zero-degree plies are overloaded in the course of the internal stress redistribution and the laminate foils. This is characterized by a sudden fiber failure, which is localized to the immediate vicinity of the fracture surface.

The coincidence of shakedown and damage ranges is expected to apply to other composite systems with annealed and as-fabricated aluminum matrices, but not to those with T6 tempered and other high-strength matrices that suffer fatigue failure well within their elastic deformation ranges.

It can be concluded from this work that, although the absolute value of the fatigue strength was dependent on the properties of the fibers, matrix fatigue properties are a controlling factor that determines the loading ranges within which composites may be safely used.

EFFECTS OF DEFECTS ON FATIGUE PROPERTIES

Since the matrix controls the fatigue fracture mechanism in metal matrix composites, any defects in the composite that promote early crack growth in the matrix should be avoided. As an example, Dvorak and Johnson (1980) observed early fatigue damage caused by the presence of surface grooves, which act as surface cracks or precipitate growth of such cracks during fatigue loading when their orientation is perpendicular to the applied load.

It is also expected that fiber properties will influence fatigue life. Bhatt and Grimes (1979) attributed poor fatigue life of MMC specimens they tested to the presence of flawed and fractured fibers created near the specimen surface by preparation techniques and to the large residual tensile stresses that can exist in fiber-reinforced matrices.

Experimental investigations by Dvorak and Tarn (1975) have shown that the characteristics of the fiber matrix interface do not appear to affect the magnitude of the axial fatigue limit of a composite. However, if the composite is loaded above its fatigue limit, the interfaces can have a very significant effect on the rate of fatigue microcrack propagation in the constituents and on the fatigue life.

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Chapter 5

DESIGN FOR FLAW CRITICALITY

The use of nondestructive tests as a method of determining the quality of structural elements has long been an accepted quality control technique. The use of nondestructive testing together with tests to destruction has been and continues to be used in metal and composite structures. The advent of advanced composites for structural applications and the complex nature of composite materials has led to the extensive use of nondestructive testing for validating the production quality of these materials.

For metallic materials, the designer of flaw critical parts is careful to select materials with superior toughness, high ductility, and resistance to crack growth. A great deal of fracture mechanics research and development have provided the engineering designer with the tools to design for flaw-critical applications. Although the designer works with inherently brittle composite materials, the laminant form is of increased toughness compared to monolithic metallic materials. In polymer composites, a great deal of effort has been expended on fracture mechanics, but thus far the theories have not been proved or widely disseminated for use by designers. This lack of information is particularly prevalent in the field of metal matrix composites, where the research is much less developed than that for polymer matrices.

APPLICATION REQUIREMENTS

To discuss designing for critical flaws in aerospace structures, it is convenient to review three classes of vehicles that differ significantly in their requirements. The three classes are aircraft, missiles (tactical and ballistic), and space structures. The aircraft designer is concerned with long periods of repetitive load environment, and therefore fatigue properties are of principal concern. This fatigue environment leads to cracks and crack propagation, so designing flaw-insensitive structures is as important as finding initial flaws. Missile load environments are normally very short, with only a few excursions approaching design loads. Thus, missile designs are not normally fatigue-critical, but load excursions close to the strain capability of the materials cause concern regarding initial defects detection. Space structure designs tend to be characterized by very long periods in a relatively benign external loads environment. Although their loads are normally small, space structures have severe requirements for dimensional stability under extreme temperature variations. An additional characteristic of space structures is that they tend to be one of a kind, so nondestructive testing is very important to providing flight-quality hardware. Defects in the space structure could also measurably affect dimensional stability.

MATERIALS APPLICATION

The types of applications in each of the three vehicle classes can be divided among primary structure, secondary structure, and joints. Primary structure is the largest and most critical structure to the vehicle's function or performance; it includes wings, fuselage, missile shell sections, and payload support sections. Primary structure receives the greatest amount of nondestructive testing because of its critical nature and its size. Secondary structure is less important because it is smaller or because it does not carry loads critical to the vehicle's performance. This type of structure includes brackets, control surfaces, and linkages. Because of its size and usually complex geometry, secondary structure tends to receive less nondestructive testing than primary structure. Joints are very important structural elements; however, their geometry tends to make them poor candidates for nondestructive testing. Because joints can transfer primary loads between elements of primary structure, attempts are often made to test these elements nondestructively, but often confirmation of their integrity is left to precise manufacturing control alone.

DESIGN METHODOLOGY

Aerospace designers have several ways to minimize the effect of flaws on the performance of a structure. They can design with known flaw-insensitive materials, they can make the designs physically tolerant of flaws, and, finally, they can require nondestructive testing of those areas of the design that require special attention during service life.

To allow the use of available NDT methods, the designer must know the kinds and sizes of defects the NDT techniques are capable of identifying. In composites, the types of defects include disbonds, delaminations, fiber discrepancies (broken or misoriented), porosity or voids, and matrix discrepancies (matrix-poor or -rich). Once the designer knows what defects nondestructive testing can find, he needs to know what effect those defects may have. This information may be obtained theoretically; however, for composites, the tendency is to develop the information empirically. When this information is available, the designer can make allowance for a particular flaw that may be critical.

The methods that the designer uses to provide a flaw-resistant structure include conservative design, extensive testing, and thorough inspection. Conservative design is not significantly different for metals, discontinuous reinforced metals, or laminated composites (polymer or metal matrix). The designs tend to be more conservative in areas where periodic inspection is not feasible and where visual inspection is difficult. The designer tends to use higher margins of safety in areas where flaws would be critical but are considered undetectable. A good example of this type of flaw is a curved beam that has failed in through-the-thickness tension that delaminates the structure but cannot be easily detected when the load is removed because the delamination closes. The designer tries to provide redundant or multiple parallel load paths for the flaw-critical areas so that a failure in one element will not result in failure of the vehicle. Wherever possible, crack arrestment is designed into the structure. Crack arrestment concepts include joints in the structure or locally increased thickness that reduces the material stresses.

Extensive testing is performed for three general purposes: to develop design allowables, including uninspectable damage; to develop accept-or-reject criteria for flaws that NDT methods can articulate; and to perform life testing or flight confidence testing on typical structures containing characteristic flaws. The design-allowables testing is performed to define the degree of degradation of properties caused by known defects. These design allowables are then used by the designer to preclude problems in those areas where flaws would cause critical structural failures. Accept-or-reject testing is normally performed on structural elements to demonstrate degradation in performance with known detectable defects. These accept-or-reject test data are often used to evaluate hardware by nondestructive testing. Life testing is full-scale testing of vehicles or subelements to more than their expected service life at accelerated rates. Often these tests are run for 2 lifetimes and then the structure is intentionally flawed and testing is continued until cumulative damage destroys it.

Thorough inspection by NDT methods provides the designer the only actual data on the exact article fabricated. These data can be used with the testing results and predicted results to determine the acceptability of the hardware.

In the development of nondestructive testing of metal matrix composites, it is important from the designers point of view, to minimize cost and fear of the unknown. Extreme NDT requirements at all levels of material and part manufacture will result in high cost for the material, which could preclude its use. The need for such extensive nondestructive testing will also tend to create distrust of the material by the designer, which may reduce its chance of application. Second, the NDT community should focus on NDT methods appropriate for structure in addition to methods for raw material. The manufacture of the structure is likely to introduce defects that may be of more consequence to performance. Third, an attempt should be made to correlate detectable defects using nondestructive testing with actual degradation as demonstrated by destructive tests. Fourth, the community should disseminate data on nondestructive testing of metal matrix composites to designers through design-oriented publications and seminars. Finally, the development and testing of fracture mechanics theories specifically for metal matrix composites should be accelerated.

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JAMES A. CORNIE is experienced in the areas of production and fabrication of fibers and matrices. He received his B.S. degree from the University of Idaho, M.S. degree from Rensselaer Polytechnic Institute, and Ph.D. from the University of Pittsburgh. He began his professional experience as an engineer, first with the Kennecott Copper Co. and then with Pratt and Whitney Aircraft. He later became senior engineer of alloy development at Astronuclear Labs, Westinghouse Electric Company and in 1977 Manager, Metal Matrix Material, Specialty Materials Division of the AVCO Corporation. He is presently Director, Metal Matrix Composites Research Projects, Department of Materials Science at M.I.T. He is a member of the Metallurgical Society of AIME and American Society for Metals.

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R. BYRON PIPES is currently a member of the National Materials Advisory Board and is recognized as an innovator in the field of metal matrix composites and nondestructive testing. He received his B.S. and M.S. degrees from Louisiana Polytechnic Institute, his M.S.E. from Princeton University, and his Ph.D. from the University of Texas. He worked as a senior structural engineer for the General Dynamics Corporation until 1972 and as Assistant Professor of Mechanical Engineering at Drexel University until 1974. He joined the faculty of the University of Delaware in 1974 as Associate Professor of Mechanical and Aerospace Engineering and advanced in 1978 to his present position at the university as Director, Center for Composite Materials.

RICHARD S. WILLIAMS has had broad experience with NDE of metal matrix composites. He attended Lowell Technological Institute where he obtained his B.S. and M.S. in mechanical engineering. He received his Ph.D. from Virginia Polytechnic Institute. He worked as an instructor at Virginia Polytechnic Institute where he also performed research in the areas of composites, mechanical behavior, fatigue, and NDE; as a research scientist at Battelle Memorial Institute, carrying out research in all areas of NDE; and at the Babcock and Wilcox Lynchburg Research Center as program manager/senior research engineer. In 1979 he began work as a senior research engineer at the United Technologies Research Center where he is involved in formulating and conducting multidisciplinary research in NDE. He has published extensively in the area of NDE and is the editor of a special issue of Materials Evaluation on Ultrasonic Imaging.

CARL H. ZWEBEN is a specialist in materials engineering and applied mechanics. After receiving his B.C.E., M.S., and Ph.D. degrees (Cooper Union, Columbia University, Brooklyn Polytechnic Institute) he joined the staff of the General Electric Company as a research engineer followed by positions as senior research engineer at the Jet Propulsion Lab, project manager with the Materials Sciences Corporation, and research associate with E. I. du Pont de Nemours and Co. His present position is with the General Electric Co. where he is a staff engineer in the composite materials and structures section of the Valley Forge Space Center.