

CHAPTER 3 EVALUATION OF REINFORCEMENT FIBERS

3.1 INTRODUCTION

This chapter describes techniques and test methods that are generally used to characterize the chemical, physical, and mechanical properties of reinforcement fibers for application in organic matrix composite materials. Reinforcements in the form of unidirectional yarns, strands, or tows, and bidirectional fabrics are covered. Sophisticated experimental techniques generally are required for fiber characterization, and test laboratories must be well-equipped and experienced for measuring fiber properties. It is also recognized that in many cases the measurement of a fiber property that manifests itself in the reinforced composite can best be accomplished with the composite. Sections 3.2 through 3.5 recommend general techniques and test methods for evaluating carbon, glass, organic (polymeric), and other specialty reinforcement fibers. Section 3.6 contains examples of test methods that can be used for evaluating fibers.

Most reinforcement fibers are surface treated or have a surface treatment (e.g., sizing) applied during their production to improve handleability and/or promote fiber-resin bonding. Surface treatments affect wettability of the fiber during impregnation as well as the dry strength and hydrolytic stability of the fiber-matrix bond during use. Because of the direct relation to composite properties, the effectiveness of any treatments to modify surface chemistry is generally measured on the composite itself by means of mechanical tests. The amount of sizing and its compositional consistency are significant in quality control of the fiber and measurement of these parameters is part of the fiber evaluation.

3.2 CHEMICAL TECHNIQUES

A wide variety of chemical and spectroscopic techniques and test methods are available to characterize the chemical structures and compositions of reinforcement fibers. Carbon fibers are found to range from 90-100% carbon. Typically, standard and intermediate modulus PAN carbon fibers are 90-95% carbon, with most of the remaining material being nitrogen. Minor constituents and trace elements can be extremely important when composites containing these fibers are considered for use at elevated temperatures (above 500°F or 260°C). Organic fibers usually contain significant amounts of hydrogen and one or more additional elements (e.g., oxygen, nitrogen, and sulfur) which can be identified by spectroscopic analysis. Glass fibers contain sulfur dioxide and usually aluminum and iron oxide. Depending upon the type of glass, calcium oxide, sodium oxide, and oxides of potassium, boron, barium, titanium, zirconium, sulfur, and arsenic may be found.

3.2.1 Elemental analysis

A variety of quantitative wet gravimetric and spectroscopic chemical analysis techniques may be applied to analyze the compositions and trace elements in fibers. ASTM Test Method C 169 may be used to determine the chemical compositions of borosilicate glass fibers (Reference 3.2.1(a)).

A suitable standardized method for carbon and hydrogen analysis, modified to handle carbon and polymeric fibers is provided by ASTM D 3178 (Reference 3.2.1(b)). Carbon and hydrogen concentrations are determined by burning a weighed quantity of sample in a closed system and fixing the products of combustion in an absorption train after complete oxidation and purification from interfering substances. Carbon and hydrogen concentrations are expressed as percentages of the total dry weight of the fiber. ASTM Method D 3174 (Reference 3.2.1(c)) describes a related test in which metallic impurities may be determined by the analysis of ash residue.

Alternatively, a variety of commercial analytical instruments are available which can quickly analyze carbon, hydrogen, nitrogen, silicon, sodium, aluminum, calcium, magnesium and other elements in reinforcement fibers. X-ray fluorescence, atomic absorption (AA), flame emission, and inductively coupled plasma emission (ICAP) spectroscopic techniques may be employed for elemental analysis. Operating instructions and method details are available from the instrument manufacturers.

Trace metallic constituents are significant in carbon and polymeric fibers because of their possible effect on the rate of fiber oxidation. The presence of metals is usually expressed as parts per million in the original dry fiber and can be determined by analyzing the ash residue. Semi-quantitative determinations are generally made using flame emission spectroscopy. When quantitative values are desired, atomic absorption methods are used. With respect to oxidation of carbon fibers, sodium is usually of most concern because of its tendency to catalyze the oxidation of carbon.

3.2.2 Titration

The potential chemical activity of surface groups on fibers may be determined by titration techniques. For example, the relative concentration of hydrolyzable groups introduced during the manufacture or post treatment of carbon fibers may be determined by measuring the pH (section 3.6.1). However, titration techniques are typically not used on commercial carbon fibers due to the low levels of surface functionality.

3.2.3 Fiber structure

X-Ray diffraction spectroscopy may be used to characterize the overall structure of crystalline or semi-crystalline fibers. The degree of crystallinity and orientation of crystallites have a direct effect on the modulus and other critical properties of carbon and polymeric fibers.

X-ray powder diffraction using commercial power supplies and diffractometer units is used to characterize the structure of carbon fibers. The fiber is ground into a fine powder and then the X-ray powder diffraction pattern is taken using $\text{CuK}\alpha$ radiation. The patterns generally undergo computer analysis to determine the following parameters:

- (a) Average graphite layer spacing: from the 002 peak position.
- (b) Average crystal size L_c : from the 002 peak width
- (c) Average crystal size L_a : from the 100 peak width.
- (d) Average lattice dimension a-axis: from the 100 peak position.
- (e) The ratio of peak area to the diffused area.
- (f) The 002 peak area to the total diffraction area.
- (g) The 100 peak area to the total diffraction area.
- (h) The ratio of the 100 to 002 peak areas.
- (i) Crystallinity index: from a comparison of the X-ray diffraction of known crystallized and amorphous carbons.

X-ray scattering of crystalline fibrous materials shows the presence of sharp and diffuse diffraction patterns which are indicative of crystal phases interdispersed with amorphous regions. The concept of the crystallinity index is derived from the fact that a portion of the scattering from a fiber is diffuse and thereby contributes to the so-called amorphous background. Thus, a simple method of estimating crystallinity is obtained by separating the diffraction pattern into crystalline (sharp) and amorphous (diffuse) components. The crystallinity index is a relative measure of crystallinity, and not an absolute numerical result, useful for correlating with physical properties of fibers.

Wide angle X-ray spectroscopy and infrared spectroscopy techniques have also been developed to determine the crystallinity and orientation of molecules in polymeric fibers. Testing and interpretation of results requires specialized equipment, sophisticated computer models, and a high level of technical expertise.

3.2.4 Fiber surface chemistry

Fibers generally are given a surface treatment to improve the adhesion between the fibers and resin matrix materials. Gases, plasmas, liquid chemical or electrolytic treatments are employed to modify fiber

surfaces. Introducing surface oxidation is perhaps the most common approach to modifying fiber surfaces.

Fiber surface structure, the modifications which surfaces undergo as a result of the different fiber surface treatments, and the relative importance of these modifications for composite properties are not well understood. This arises because of the small surface areas involved (0.5 to 1.5 m²/g) and the very low concentrations of functional groups. If 20% of the surface was covered by one particular species, this would only amount to 1 μmole of chemical groups per gram of fiber. Surface characterization should be carried out on fibers which have not been sized. Residual size from solvent desized fiber can interfere with most techniques, while pyrolysis techniques may alter the fiber surface due to oxidation and char products.

The following techniques have been used for characterizing fiber surfaces:

- (a) X-ray diffraction - provides information relating to crystallite size and orientation, degree of graphitization, and micropore characteristics.
- (b) Electron diffraction - gives crystallite orientation, three-dimensional order, and degree of graphitization. (better for surfaces since penetration is only 1000 Å).
- (c) Transmission Electron Microscopy (TEM) - provides the highest resolution of any of the microscopic techniques routinely available. Ultramicrotomy can be used to prepare specimens, typically about 50 nanometers thick, for direct TEM analysis of the fiber surfaces. TEM provides information about surface fine structure and show fibrils and needle-like pores.
- (d) Scanning Electron Microscopy (SEM) - Gives structural and surface features. SEM is a useful technique for determining fiber diameters and identifying morphological characteristics (scales, chips, deposits, pits) on fiber surfaces.
- (e) Electron Spin Resonance (ESR) Spectroscopy - gives crystallite orientation.
- (f) X-ray Photoelectron Spectroscopy (XPS) or Electron Spectroscopy for Chemical Analysis (ESCA) - measures the binding energy of core electrons in atoms excited by low energy X-rays. Changes in the chemical environment of a surface region 10-15 nanometers thick (the first few atomic layers) are revealed by slight shifts in the energy of these core electrons giving information on functional group types and concentrations. The surface sensitivity arises because the depth of the electrons is between 1 and 2 nanometers.

The ratios of total oxygen to total carbon and of oxidized carbon (including hydroxyl, ether, ester, carbonyl and carboxy functional groups) to total carbon may be determined in carbon fibers using XPS or ESCA.

- (g) Auger Electron Spectroscopy (AES) - directs high energy electrons (1-5 KeV) onto surfaces to create vacancies in the core levels of atoms. These vacancies represent excited ions which may undergo de-excitation and thereby create Auger electrons. By analyzing the characteristic energies of all the back-scattered Auger electrons in the energy range 0-1 KeV, the elemental composition of the first 30 or 40 atomic layers (about 30 nanometers) is possible and in some cases molecular information can be obtained from analysis of data.
- (h) Ion Scattering Spectroscopy (ISS) - uses an ion as a molecular probe to identify elements on the outermost surface layer. Only atomic information can be obtained and sensitivity depends upon the atomic element.

- (i) Secondary Ion Mass Spectroscopy (SIMS) - uses a controlled sputtering process with accelerated ions to remove surface atomic layers for direct analysis by mass spectroscopy. SIMS can be used to identify surface molecules and determine their concentrations.
- (j) Infrared Spectroscopy (IRS) or Fourier Transform IRS (FTIRS) - absorption vibrational spectroscopy technique to obtain molecular information about surface composition. IRS yields both qualitative and quantitative information relating to the chemical composition of surface molecules. The quality of the IR analysis depends on the fiber composition and is directly related to the care taken during sample preparation.

For fibers with diameters between 0.015 and 0.03 mm, no sample preparation is required if an IR microscope is available to examine fibers directly. Organic fibers may be pressed (up to 1000/m²) into a film of fiber grids.

- (k) Laser Raman spectroscopy - absorption/vibrational spectroscopic technique which complements IR and is relatively simple to apply. Little or no sample preparation is necessary. Fibers can be oriented in the path of the incident beam for direct analysis. Fiber sample must be stable to the high intensity incident light and should not contain species that fluoresce.
- (l) Contact angle and wetting measurements - provide an indirect measurement of fiber surface free energy for use in predicting interfacial compatibility and thermodynamic equilibrium with matrix materials. Contact angle and wetting measurement information can be obtained by direct measurement of contact angle, mass pick-up, or surface velocity. Measurement of contact angles on small diameter fibers (< 10 microns) is difficult if done optically. If a fiber's dimensions are known, a simple force balance may be used to determine the contact angle by measuring the force induced by immersing the fiber into a liquid of known surface free energy. The apparatus usually employed for this test is the Wilhelmy balance (Reference 3.2.4(a)).

Contact angles θ also may be measured indirectly by the micro-Wilhelmy technique (References 3.2.4(b-e)). A single fiber is partially immersed in a liquid and the force exerted on the fiber due to the surface tension of the liquid is measured. The contact angle is determined from the relationship $F = C\gamma_{LV} \cos\theta$ where F is the force measured corrected for buoyancy, C is the circumference of the fiber, and γ_{LV} is the surface tension of the liquid. The results may be used to determine the fiber surface free energy and the contributions of polar and dispersive components to the free energy (References 3.2.4(c) and (d)).

- (m) Physisorption and chemisorption measurements - adsorption of inert gas or organic molecules can be used to measure fiber surface area. To obtain accurate estimates of surface area, it is important that there is complete monolayer coverage of the surface, that the area occupied by the adsorbed gas is known and that significant amounts of the gas are not taken up in micropores. Additional complications arise when the adsorption of organic molecules is used in place of gas adsorption, since it may be necessary to know the orientation of the adsorbed molecules to calculate surface area. Adsorption may also occur only at specific active sites and, if solutions are used, solvent molecules may be adsorbed as well.

The chemical reactivity of fiber surfaces can be determined by oxygen chemisorption and desorption measurements. Topographical changes (e.g., pores, cracks and fissures) caused by surface treatments often can be readily detected by adsorption measurements. Flow microcalorimetry is a useful technique for directly measuring heats of adsorption (Reference 3.2.4(f)).

- (n) Thermal desorption measurements - desorption of volatile products from fibers by heat treatment in vacuo. Thermal gravimetric analysis (TGA), gas chromatography (GC), mass spectroscopy (MS), infrared spectroscopy (IRS) analysis or combinations of pyrolysis GC/MS or TGA/IRS may be used to identify components desorbed from fiber surfaces. Below 150°C, CO, NH, CH and various organic molecules are observed depending upon the fiber type.

- (o) Chemical identification of functional groups by titrimetric, coulometric and radiographic techniques.

3.2.5 Sizing content and composition

The amount of sizing contained on fibers is expressed as a percentage of the dry sized fiber weight. It is generally determined by extracting the fibers with a heated solvent; then the cleaned fibers are washed, dried, and weighed. ASTM Test Method C 613 (Reference 3.2.5) describes a suitable method utilizing Soxhlet extraction equipment; however, similar extractions using a laboratory hot plate and beaker are also common. The selection of a solvent which quantitatively removes all the sizing but not does dissolve the fiber is essential for accuracy in this determination.

Thermal removal techniques are also utilized and are most practical for the more difficult soluble sizings. Time, temperature, and atmosphere conditions must be predetermined to ensure the sizing is removed without seriously affecting the fiber. The precise amounts of residue from decomposition of the sizing and weight loss of the fibers due to oxidation must also be known from control tests for greatest accuracy. SACMA recommended test method SRM 14-90 "Determination of Sizing Content on Carbon Fibers" describes a pyrolysis technique for carbon fibers.

Sizing compositions and lot-to-lot chemical consistency may be determined by spectroscopic and chromatographic analysis of materials isolated by extracting the fibers with a suitable solvent. Acetone, tetrahydrofuran and methylene chloride are commonly used solvents for extraction. Liquid and gas chromatography and diffuse infrared spectroscopy are used to analyze or "fingerprint" the chemical compositions of extracts.

3.2.6 Moisture content

The moisture content or moisture regain of fibers or textiles may be determined using the procedure shown in Section 3.6.3. Care must be taken when applying the procedure since volatile materials in addition to moisture may be removed. If possible, tests should be performed on fibers that have not been sized. Moisture content is expressed as weight percentage moisture based upon the dry weight of the specimen.

3.2.7 Thermal stability and oxidative resistance

The susceptibility of fibers and fiber surface to oxidation is measured as weight loss under given conditions of time, temperature, and atmosphere. This is especially important in the evaluation of carbon and organic fibers considered for use in plastics exposed to elevated temperatures since it contributes to the long term degradation of composite properties. Thermal gravimetric analysis (TGA) may be used to determine the thermal decomposition temperature T_d of carbon and organic fibers and estimate the relative amounts of volatile, organic additives and inorganic residues.

A standard method for determining the weight loss of carbon fibers is given in ASTM Test Method D 4102 (Reference 3.2.7(a)). Variations in this test method regarding exposure of fibers have been studied and give similar results (Reference 3.2.7(b)). In order to minimize variability in test results, proper control of gas flow rates and currents is critical when performing TGA analyses.

3.2.8 Chemical resistance

This section reserved for future use.

3.3 PHYSICAL TECHNIQUES (INTRINSIC)

The physical properties of fibers of importance in their applications in polymer matrix composites fall into two categories - those inherent in the filament itself (intrinsic), and those derived from the construction of filaments into yarns, tows, or fabrics (extrinsic). The former includes density, diameter, and electrical resistivity; the latter includes yield, cross-sectional area, twist, fabric construction and areal weight. Density and the derived properties are used in the calculations required for the construction and analysis of the composite products. Density and yield are useful measures of quality assurance. Filament diameter and electrical resistivity are important for the nonstructural aspects of aerospace and aircraft applications.

3.3.1 Filament diameter

The average diameter of fibers may be determined by using an indexing microscope fitted with an image splitting eyepiece or from a photomicrograph of the cross-sectional view of a group of mounted fibers. Since fibers are not always true cylinders, effective diameters may be calculated from the total cross-sectional area of the yarn or tow and dividing by the number of filaments in the bundle. The cross-sectional area may also be estimated from the ratio of mass per unit length to density. For irregular, but characteristically-shaped, fibers an area factor may be required in calculating the average fiber diameter.

Optical microscopy can provide information about fiber diameter and variation in diameter with length. The upper limit of resolution of the optical microscope is about one-tenth of a micron; hence features less than one micron can not be well-characterized by optical microscopy. A detailed procedure for the determination of fiber diameter is described in Section 3.6.4.

Other techniques, such as scanning electron microscopy (SEM), provide much higher resolution than optical microscopy for determining fiber diameter and cross-sectional characteristics. Features of fiber surfaces down to the 5 nanometer level can be observed. In addition, the large depth of field provided by SEM helps defined three-dimensional characteristics on fiber surfaces and define fiber topography.

3.3.2 Density of fibers

3.3.2.1 Overview

Fiber density is not only an important quality control parameter in fiber manufacture, it is required for determination of the void content of the fibrous composite, as described in ASTM D 2734, "Void Content of Reinforced Plastics" (Reference 3.3.2.1(a)). Fiber density can also be used as a distinguishing parameter to identify a fiber. For example, fiber density results can readily differentiate between E and S-2 glass (E glass is 2.54 g/cm^3 (0.092 lb/in^3), S-2 is 2.485 g/cm^3 (0.090 lb/in^3)).

With few exceptions, the determination of density is accomplished indirectly by measuring the volume and weight of a representative sample of the fiber, and then combining these values to calculate density. The weight measurement is most easily obtained by using a quality analytical balance. To determine volume, however, there are several approaches used. The most common approach uses simple Archimedes methods involving displacement of liquids of known density. Direct measurement of density can be made by observation of the level to which the test material sinks in a density-graded liquid (Reference 3.3.2.1(b)).

Liquids are used almost exclusively in displacement techniques for the determination of volume. However, there are advantages to using a gas medium in place of liquid to determine the volume of fiber. One advantage is minimization of errors associated with liquid surface tension. The gas displacement approach is often referred to as helium pycnometry. When a gas displacement approach is used, the test specimen volume is determined by measuring pressure changes of a confined amount of a gas that behaves as an ideal gas at room temperature (preferably high purity helium). Helium pycnometry is not a recognized test method for measuring the volume and density of fibers, yet it has been demonstrated to be a viable technique (References 3.3.2.1(c) and (d)). As no test standard or guidelines exist for this

method as applied to fiber, a test procedure has been developed within the MIL-HDBK-17 Testing Working Group (see Section 6.4.4.4.1).

ASTM Test Method D 3800 (Reference 3.3.2.1(e)) deals specifically with obtaining the density of fibers. This standard covers three different liquid displacement procedures: Procedure A, which is very similar to the D 792 liquid displacement method (Reference 3.3.2.1(f)); Procedure B, in which a low-density liquid is slowly mixed with a high-density liquid (containing the fibers) until the fibers become suspended; and Procedure C, which simply references D 1505, which is a density-gradient method.

For detailed guidance on D 1505 and helium pycnometry, the reader is referred to Sections 6.4.4.3 through 6.4.4.5 of this volume of the Handbook. Note that Section 6.4.4 refers specifically to composites, but the methods discussed are fully applicable to fiber measurement except as noted below in Sections 3.3.2.2 through 3.3.2.3.

3.3.2.2 ASTM D 3800, Standard Test Method for Density of High-Modulus Fibers

The approach taken in ASTM D 3800 is threefold. Procedure A is identical to D 792 except that the immersion fluids recommended have only fibers in mind. The concern is complete fiber wetting and avoiding entrapped microbubbles. Procedure B relies on careful mixing of two liquids of different densities (with the fiber immersed). When the fibers are suspended in the mixed liquid a hydrometer or liquid pycnometer is used to determine the density of the liquid. The density of the suspended fiber is equal to that of the liquid. Procedure C is D 1505 inserted as a part of D 3800 by reference.

Given that apparatus and procedures are identical to D 792 for the liquid displacement procedure (Procedure A), and that Procedures B and C have much in common with D 1505, the reader is referred to Sections 6.4.4.2 through 6.4.4.5. Here, only those test aspects peculiar to fibers are discussed.

The experimenter needs to be mindful to avoid entrapped bubbles, liquid absorption, and problems involving the fiber sizing coating (if any). Common sense immediately flags roving as a difficult fiber form to wet out, yet complete wetout is required to produce meaningful data. Pay close attention to the inter-filament regions. In D 1505 the problem is not as severe because the fibers can be cut and/or spread out prior to insertion. Since the measurement is direct the size of the fiber sample is irrelevant. Immersing many small fiber fragments allows for direct verification of density variations of the fiber, keeping in mind that small fragments may take hours to sink to their equilibrium density level. It can not be emphasized enough that complete wetout must be achieved. Use of high-wetting, vacuum-degassed liquids go a long way to this end. Remember that the fibers are a prime geometry for nucleation of gas bubbles out of solution. If the liquid is not fully degassed a bubble-free roving can quickly form new bubbles.

The surface area to volume ratio of composite fibers is extremely high. For cylindrical shapes, $S.A./V=2/R$, where R, the radius, is only several microns. For a 0.028 mil (7 micron) fiber the ratio is 143,000 to 1. It is, therefore, very important to ensure compatibility between the fiber and liquid. Glass and polyethylene fibers are fairly immune in this regard; however, aramid, for example, is certainly not. The liquid immersion time should be kept to a minimum to avoid liquid diffusion into the fiber.

The mistake is often made of thinking of the fiber by itself, when in reality it is usually coated with an interfacial sizing agent (to promote improved bonding with the matrix resin). It is good practice to re-search the sizing agent, as it is a completely different material than the fiber (with different absorption and chemical characteristics). Since the sizing is applied to the outer surface of the fiber even the volume of a thin coat quickly becomes significant. For example, a 0.028 mil (7 micron) diameter carbon fiber with a typical coating of 1% sizing agent on a weight basis (with assumed density of 1.2 g/cm³ (0.043 lb/in³)) gives a final product which is 98.5% fiber and 1.5% sizing on a volume basis. For precision work, strip the sizing agent off the fiber before measuring fiber density.

3.3.2.3 Recommended procedure changes to Section 6.6.4.4.1 (helium pycnometry) for use in measuring fiber density

In general, it would seem that helium pycnometry lends itself to the measurement of fiber volume/density (although this has yet to be rigorously tested). This is mainly due to the fact that the inert gas medium circumvents the issue of fiber wetout, which is a concern when using any of the liquid immersion methods. Recommended changes to the procedure in Section 6.6.4.4.1 are as follows:

- To prepare the fiber specimens, cut them to the height of the sample cell and stand them on end to get best packing.
- Fill the cell volume to a minimum of 30% of its full capacity.
- Precondition the fibers in the same manner as for immersion testing.
- Follow the instructions under step 2.

3.3.2.4 Density test methods for MIL-HDBK-17 data submittal

Data produced by the following test methods (Table 3.3.2.4) are currently being accepted by MIL-HDBK-17 for consideration for inclusion in Volume 2.

TABLE 3.3.2.4 Fiber density test methods for MIL-HDBK-17 data submittal.

Property	Symbol	Fully Approved, Interim, and Screening Data	Screening Data Only
Density	ρ	D 3800A, D 3800C, D 1505, 3.3.2.3*	D 3800B**

*When this method is used to generate data for subsequent determination of composite void volume, the test specimen must occupy at least 30% of the test cell volume.

**Data from this method is not recommended for use in determining void volume of composites due to precision limitations.

3.3.3 Electrical resistivity

The determination of electrical resistivity is recommended as a control measure for checking processing temperature and to determine compliance with specific resistance specifications, where required. Electrical resistivity is one of the properties dramatically affected by the structural anisotropy of carbon fibers. Measurements can be made on either a single filament or a yarn. The measured value is resistance per given length of fiber as read on an ohm meter or similar device. The contact resistance can be eliminated by obtaining the resistance for two different lengths of fiber and calculating the difference due to the longer length. This difference is then converted to resistance per unit length and then multiplied by the area of the fiber or yarn bundle expressed in consistent units. Resistivity is expressed as ohm-centimeter, ohm-meter, or ohm-inches and refers to the value in the axial direction. Transverse resistivity is seldom reported. A procedure for determining the electrical resistance of carbon cloth or felt is described in Section 3.6.5.

3.3.4 Coefficient of thermal expansion

Standardized methods for measuring the coefficient of thermal expansion (CTE) of the fibers are not generally available although good correlations between laboratories making these measurements do exist. CTE's are directionally dependent, highly influenced by the anisotropy of fibers. Carbon fibers typically have a negative axial CTE and a slightly positive transverse CTE. Commercial instruments (e.g., DuPont Model 943 Thermomechanical Analyzer, or equivalent) can be used directly or modified to measure axial CTE.

The CTE of the fiber can also be derived from measurements made on composites with unidirectional reinforcement. Laser interferometry and dilatometry are the techniques most frequently used. Other techniques, including some applied to the unimpregnated fiber, have also been found satisfactory. When testing the composite, the unidirectional fibers may be oriented parallel or perpendicular to the direction of measurement to obtain the axial or transverse CTE. To perform the analysis, the modulus of the fiber, the modulus and CTE of the matrix, and the fiber loading must be known. It may be desirable to perform the measurements on composites with different fiber loadings in order to check the results.

3.3.5 Thermal conductivity

The thermal conductivity of fibers is generally determined analytically from measurements of axial thermal conductivity on unidirectional reinforced composites. However, some measurements have been made on both fiber bundles and single filaments. These have agreed quite well with values determined from composite measurements (Reference 3.3.5(a)). Both types of measurements require considerable operator skill and sophisticated equipment, and are perhaps best left to the thermophysics laboratory. A well defined relationship between axial thermal conductivity and axial electrical conductivity (or resistivity) has been developed for a wide range of carbon fibers. Since electrical resistivity is relatively easy to measure, reasonable estimates of thermal conductivity can be made for electrical resistivity measurements (Reference 3.3.5(b)). Transverse thermal conductivity can be determined for thin composites using a pulsed laser technique to measure thermal diffusivity. The thermal conductivity can then be calculated if the specific heat of the fiber is known.

3.3.6 Specific heat

This property is measured in a calorimeter such as described in ASTM D 2766 (Reference 3.3.6). This also is not a simple measurement and is best left to the experienced laboratory.

3.3.7 Thermal transition temperatures

Differential scanning calorimetry (DSC), differential thermal analysis (DTA) or thermal mechanical analysis (TMA) instrumentation may be applied to measure the glass transition temperature T_g and, if the fiber is semi-crystalline, its crystalline melting temperature T_m . General procedures for measuring T_g and T_m of organic fibers are given in ASTM standards D 3417 and D 3418 (References 3.3.7(a) and (b)).

3.4 PHYSICAL TECHNIQUES (EXTRINSIC)

3.4.1 Yield of yarn, strand, or roving

Yield is generally expressed as length per unit weight, such as yards per lb, or as its reciprocal, linear density, expressed as weight per unit length. The latter is normally the measured value and is determined by accurately weighing in air a precise length of yarn, strand, and roving.

3.4.2 Cross-sectional area of yarn or tow

This property is calculated rather than measured. However, it is very useful in subsequent calculations of fiber loadings in prepregs and composites as well as in calculations for other physical and thermophysical properties. Often it is considered a quality assurance criterion for fiber manufacture. The cross-sectional area is determined by dividing the linear density, weight per unit length, by the volumetric density, weight per unit volume, using consistent units. It should be noted that this value includes only the cumulative total of the cross-sectional areas of all the individual filaments within the bundle. The cross-sectional area is not affected by any space between filaments nor related to any calculations based on yarn or bundle "diameter".

3.4.3 Twist of yarn

Twist is defined as the number of turns about its axis per unit length in a yarn or other textile strand. Twist is sometimes desirable to improve handleability and, at other times, undesirable because it restricts spreading of the yarn or tow. It can be measured according to the direct procedure described in ASTM D 1423 (Reference 3.4.3).

3.4.4 Fabric construction

Properties of fabrics such as handleability, drapability, physical stability, thickness, and the effectiveness of the translation of fiber properties to the fabric are all dependent on fabric construction. For the purpose of this document, fabric construction is defined according to the fiber used (by type and filament count), the weave style such as "plain" or "satin", and the number of yarns per inch of fabric in both warp and fill directions. The most common weave styles employed for carbon fabrics used in aircraft and aerospace applications are plain weave, crowfoot satin, five harness satin, and eight harness satin. For a given yarn, fabric physical stability decreases and drapability increases progressively from the plain weave to the eight harness satin weave. In order to maintain a satisfactory level of stability, more yarns per inch must be added progressively toward the 8-harness satin weave fabric, thus the lightest weight fabrics are of plain weave style. There are many construction-related tests applied in the textile industry which are beyond the scope of this document. Essential standards for measure of construction are Determination of Yarn Count (ASTM D 3775), Length (ASTM D 3773), Width (ASTM D 3774) and Weight (ASTM D 3776) (References 3.4.4(a) - (d)). Additional information on weaves is provided in Volume 3, Section 2.5.1.

3.4.5 Fabric areal density

This property, although related to the yarn count previously described, is itself useful in calculations for composite construction and analysis. Expressed as weight per unit area of fabric, fabric areal density along with the fiber density governs the thickness of a cured ply of impregnated fabric at a given fiber volume loading. It is measured according to the method described in ASTM D 3776 (Reference 3.4.4(d)).

3.5 MECHANICAL TESTING OF FIBERS

3.5.1 Tensile properties

It is important to note that the fiber stress at specimen failure is test dependent. For example, Table 3.5.1 shows the difference in fiber tensile stress at failure for typical carbon fibers tested as a filament, an impregnated tow, and a unidirectional laminate. These data reflect the fact that composite tensile strength depends upon many factors, including interface characteristics, as well as fiber and matrix properties. These data emphasize the need to define the objective of fiber testing. Thus, for acceptance testing, it is recommended that fiber strength be measured on a material form representative of composite behavior. For carbon fibers, an impregnated tow test is recommended; for boron fibers, single filament tests are recommended.

TABLE 3.5.1 *Effect of test method on measured tensile strength.*

TEST	Nominal Measured Fiber Tensile Strength			
	Typical Carbon Fiber Standard Modulus		Typical Carbon Fiber Intermediate Modulus	
	ksi	MPa	ksi	MPa
Filament	595	4100	780	5380
Tow	580	4000	790	5450
Laminate	555	3830	665	4590

3.5.1.1 Filament tensile testing

Single filament tensile properties can be determined using ASTM D 3379, Tensile Strength and Young's Modulus for High-Modulus Single-Filament Materials (Reference 3.5.1.1). The following summarizes this method:

A random selection of single filaments is made from the material to be tested. The filaments are centerline mounted on special slotted tabs. The tabs are gripped so that the test specimen is aligned axially in the jaws of a constant speed movable crosshead test machine, and stressed to failure.

For this test method, filament cross-sectional areas are determined by planimeter measurements of a representative number of filament cross-sections as displayed on highly magnified photomicrographs. Alternative methods of area determination, such as optical gages, image-splitting microscope, linear weight-density method, etc., may also be used.

Tensile strength and Young's modulus are calculated from the load-elongation records and the cross-sectional area measurements. The specimen is shown in Figure 3.5.1.1.

3.5.1.2 Tow tensile testing

ASTM D 4018, Tensile Properties of Continuous Filament Carbon and Graphite Yarns, Strands, Rovings, and Tows (Reference 3.5.1.2) or its equivalent is recommended for carbon and graphite. The following summarizes this method:

Properties are determined by tensile loading to failure of resin impregnated yarns, strands, rovings, or tows. The purpose of the impregnating resin is to provide the yarn, strand, roving, or tow, when cured, with sufficient mechanical strength to produce a rigid test specimen capable of sustaining uniform loading of the individual filaments in the specimen. To minimize the effects of the impregnating resin on the tensile properties, the following should be observed:

- The resin should be compatible with the fiber.
- The amount of resin in the cured specimen (resin content) should be the minimum required to produce a useful test specimen.
- The individual filaments of yarn, strand, roving, or tow should be well collimated.
- The strain capability of the resin should be significantly greater than the strain capability of the filaments.

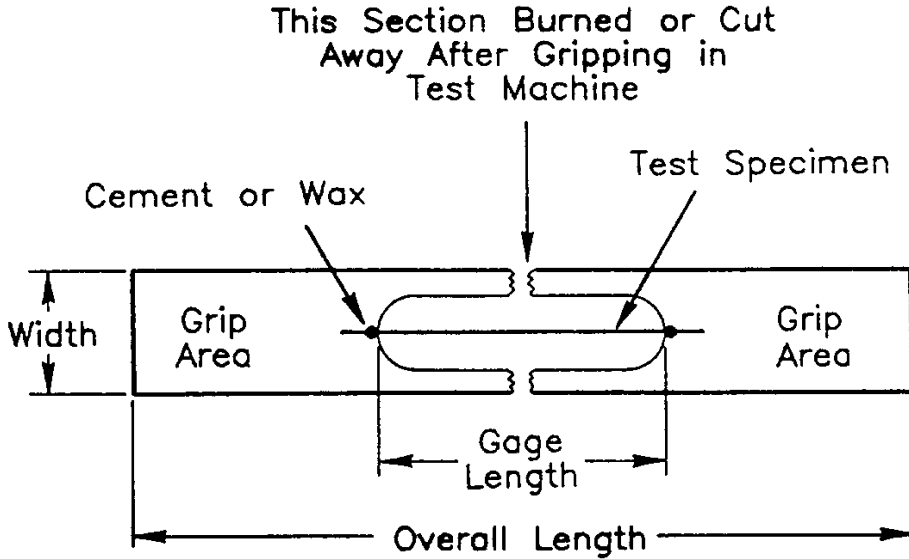


FIGURE 3.5.1.1 Typical specimen mounting method (Reference 3.5.1.1).

ASTM D 4018 Method I test specimens require a special cast-resin end tab and grip design (Figures 3.5.1.2(a) and (b)), to prevent specimen slippage in the grips under high loads. Alternative methods of specimen mounting with end tabs are acceptable, provided that test specimens maintain axial alignment on the test machine centerline, and they do not slip in the grips at high loads.

Method II test specimens require no special gripping mechanisms. Standard rubber-faced jaws should be adequate.

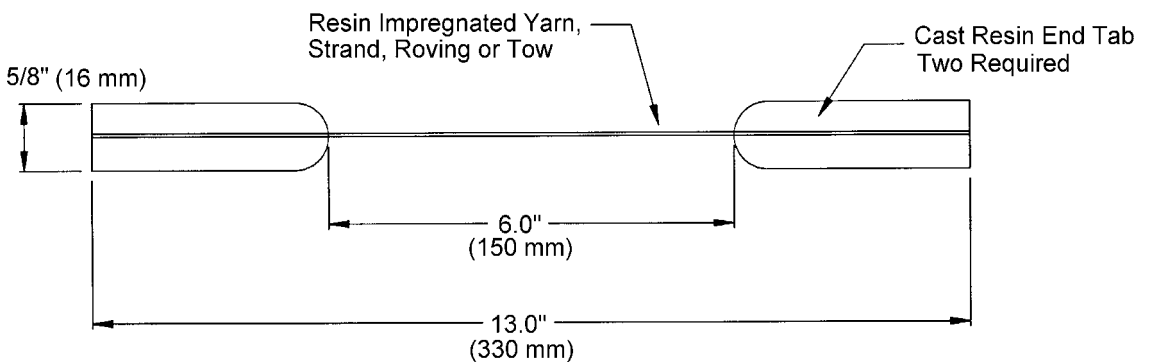


FIGURE 3.5.1.2(a) Test specimen with cast-resin tabs (Reference 3.5.1.2).

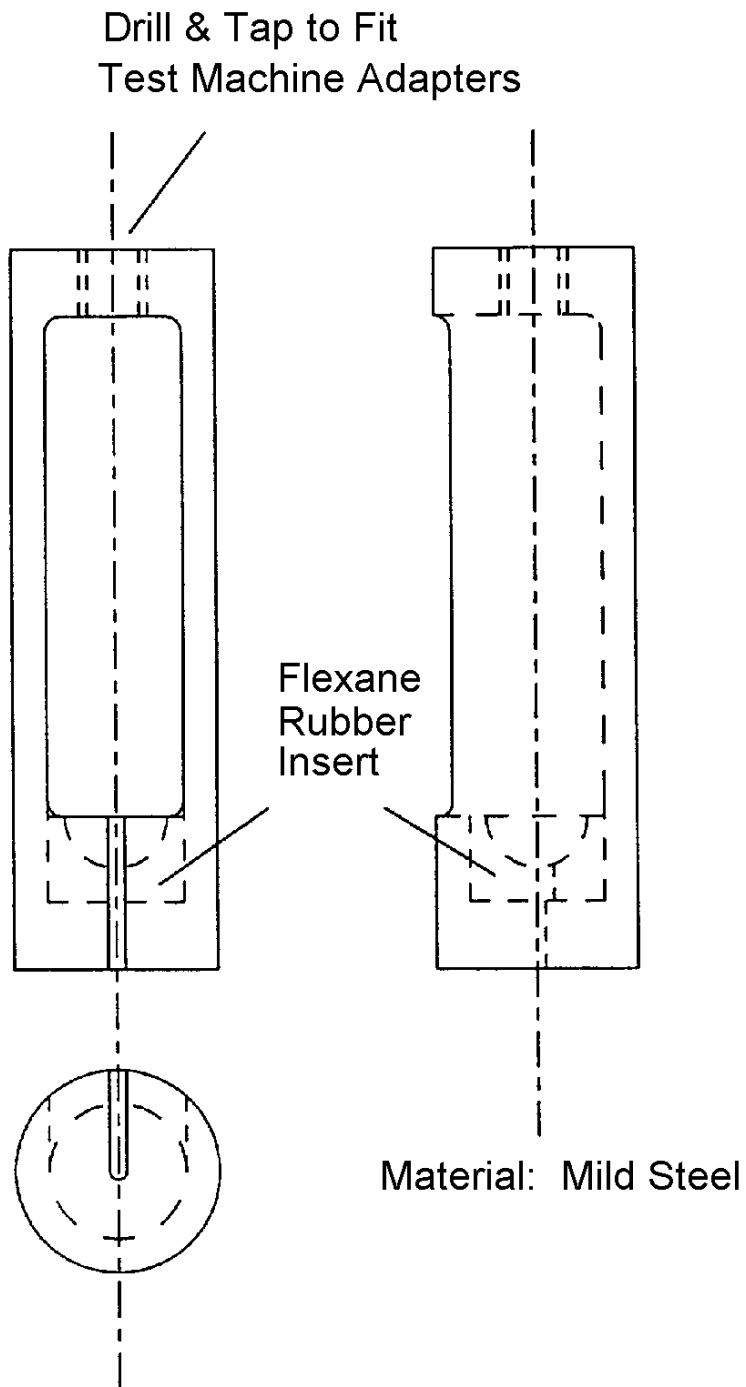


FIGURE 3.5.1.2(b) Grips for high load tensile specimen (Reference 3.5.1.2).

3.5.1.3 Fiber properties from unidirectional laminate tests

The most general representative procedure for the measurement of composite properties is to combine fiber and resin and test as a cured laminate. It is important to understand that laminate properties are a function of both fiber and resin. Table 3.5.1.3 shows the dependence of measured mechanical properties with various modified epoxy resins. Another factor to consider is the fiber volume fraction of the laminate. A fiber volume of 55% to 65% has been found to allow consistent measurement of normalized fiber properties for carbon fiber laminates. Since the objective is to determine fiber properties, the data must be normalized to 100% fiber volume. This is done simply by the following equation:

$$\text{Property (100\%)} = \frac{\text{Property} \times 100}{\text{Fiber Volume}} \quad 3.5.1.3$$

Laminate testing should be conducted per ASTM D 3039 (Reference 3.5.1.3). Laminate mechanical testing is further discussed in Section 6.6.

TABLE 3.5.1.3 Effects of resin on laminate properties.

FIBER	RESIN	TENSILE STRENGTH,		TENSILE MODULUS,	
		(ksi)	(MPa)	(Msi)	(GPa)
AS4	A	527	3630	32.1	221
AS4	B	500	3450	32.7	225
AS4	C	435	3000	32.4	223
AS4	D	432	2980	31.9	220

Tensile strength and modulus data normalized to 100% fiber volume

3.5.2 Filament compression testing

Dynamic recoil tests can be utilized to measure compressive strengths of single filaments. The test method is currently under development and is not in general use.

3.6 TEST METHODS

3.6.1 Determination of pH

(Reference 3.6.1)

3.6.1.1 Scope

This method describes a procedure for determining the pH of carbon and graphite fibers and fabrics by means of a pH meter. Measurements should be made on fibers that have not been sized. Due to the small amount of surface functionality on commercial fibers, these measurements require extreme care.

3.6.1.2 Apparatus

The apparatus needed for this procedure is as follows:

1. A pH meter equipped with glass and calomel electrodes or a single combination electrode which is preferable. It should have an accuracy of ± 0.005 pH and conform to the requirements in the Method for Determination of pH of Aqueous Solutions with the Glass Electrode ASTM E-70.
2. Lipless beakers 100-ml. capacity with cover glasses.
3. Hot plate.
4. Shears for cutting samples.
5. Large pyrex flask one to two liters capacity for boiled distilled water. The pH of this water should be between 6.9 and 7.1 at 77°F (25°C). If it is impossible to meet these limits by boiling, the pH may be adjusted with extremely weak NaOH or HCl.

3.6.1.3 Procedure

1. Prepare cloth samples by shearing into small (1/2" to 3/4") squares sufficient quantity to make 3.0 grams. Prepare yarn by cutting the sample into pieces 1/2" to 3/4" in length.
2. To 3 grams of sample add 30 ml. of the boiled distilled water, cover with a watch glass and boil very gently for 15 minutes. The use of Berzelius or liplless beakers prevents excessive loss of water. At the end of 15 minutes approximately 4 or 5 ml. of slurry should remain.
3. Set the covered beakers in a tray of cold water and cool to room temperature. Keep the beakers covered to prevent the absorption of chemical fumes that may be present in the room. After cooling remove the cover glasses but do not wash down.
4. When all is in readiness for the test, standardize the pH meter by use of a reliable buffer. Place buffer in a beaker, immerse the electrodes and adjust the meter to exactly the same value. A buffer should be chosen with a pH value in the same range as the sample to be tested. The temperature of the buffer and the sample should be the same temperature within $\pm 1^\circ$.
5. After the meter is adjusted, remove the electrodes from the buffer, rinse thoroughly with distilled water and wipe dry with clean absorbent tissue.
6. Place the electrodes in the slurry and rotate the beaker gently in alternate directions until a constant pH value is obtained.

3.6.2 Determination of amount of sizing on carbon fibers

3.6.2.1 Scope

This method describes the procedures for determining the sizing on carbon fibers, expressed as a percent of yarn weight.

3.6.2.2 Apparatus

The following equipment is needed for this procedure:

1. Balance - Analytical, Mettler Model B5-H26. Scientific Products Catalog No. B1253, or equivalent.
2. Desiccator - Scheibler including Coors desiccator plate, 250 mm I.D. Scientific Products Catalog No. D1450-5, or equivalent.

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3. Crucible - Coors, 40 ml Cap, 47mm rim dia., 40 ml h. Scientific Products Catalog No. C8450-8, or equivalent.
4. Muffle Furnace - Thermolyne, Model No. F-A1730. Maximum temp. 2000°F. Chamber Dimensions: 9 1/2"W x 8 1/2"H x 13 1/2"D, or equivalent.
5. Sagger - Stainless steel (16 gage). Dimensions: 9"W x 3"H x 10"D, with a snug fitting stainless steel cover having a 1/2" hangover on all sides. Sagger must have a 1/8" stainless steel tube connected into it for purposes of nitrogen purging. In house fabricated.

3.6.2.3 *Materials*

The following materials are needed for this procedure:

1. Drierite or equivalent - Both indicating and non-indicating crystals.
2. Nitrogen Gas - Standard purity.

3.6.2.4 *Procedure*

1. Wind approximately .003 lb. (1.5g) of sample yarn into a small ~.98-1.57 in. dia. (25-40 mm dia.) coil and place it in a desiccator for 2 hours.
2. Using clean dry forceps, remove the sample coiled from the desiccator and weigh to nearest 0.1 mg. Record as W_1 .
3. Obtain a clean dry crucible from the desiccator and place the sample coil in it. Weigh crucible plus yarn and record as W_2 . NOTE: Wear clean dry cotton gloves to prevent any moisture from being picked up by the crucible.
4. Place the crucible plus sample in the sagger and cover it with lid. A stainless steel shelf with twelve 1-3/4" Dia. holes located 3/4" from the bottom of the sagger is suggested to prevent crucibles from overturning.
5. Purge the sagger with nitrogen at a rate of 7.5 S.C.F.H. for a minimum of 45 minutes.
6. While system is purging, set the control on the muffle furnace to 842°F (450°C) and turn on.
7. When purging time is complete and the furnace is at temperature, place the sagger in the furnace and heat for 1 hour. Note, for safety, wear protective asbestos gloves or equivalent when inserting or removing the sagger from the hot muffle furnace. The N_2 purge is continued throughout the heating and cool-down phases of this test.
8. After heating for 1 hour, remove the sagger from the furnace and place it in protected cool-down area.
9. Remove the crucible from the sagger and place it in the desiccator to cool to room temperature.
10. When cool, weigh crucible plus sample and record as W_3 .

3.6.2.5 *Calculation*

Calculate the amount of sizing by determining the percent weight loss as follows:

$$\text{Sizing Content} = \frac{W_2 - W_3}{W_1} \times 100 \quad 3.6.2.5$$

3.6.2.6 *Preparation of crucibles for reuse*

Before reusing crucibles, burn off any residue by placing them in the muffle furnace and heating them at 1292°F (700°C) in air for at least 2 hours. After the crucibles are removed from the furnace and cool to room temperature, blow them out with clean compressed air. Store clean crucibles in the desiccator.

3.6.3 **Determination of moisture content or moisture regain**

3.6.3.1 *Scope*

This method may be used to determine the amount of moisture in a textile either as it is received or when it is in moisture equilibrium for testing in the standard atmosphere as defined in the definitions of Terms Relating to Textile Materials (ASTM D 123, Reference 3.6.3.1).

3.6.3.2 *Apparatus*

The following equipment is needed for this procedure:

1. Weighing Bottle, glass, approximately 100-ml. capacity, fitted with a ground-glass cover, or an aluminum weighing can, approximately 100-ml. capacity, and having a tight-fitting cover.
2. Desiccator, containing anhydrous calcium chloride (CaCl_2) or other suitable dehydrating agent.
3. Chemical Balance, capable of weighing to 0.5 mg.
4. Oven, maintained at 221-230°F (105-110°C). Note that special equipment for drying specimens to constant weight, which is generally available in textile laboratories (conditioning ovens, etc.) may also be used. The apparatus here and the procedure described in Section 3.6.3.4 are provided for laboratories without such special equipment.

3.6.3.3 *Sample preparation*

1. Cut samples for test. Approximately 2 grams are required. When sampling cloth use the Alfred Sutler Company sample cutter or equivalent, which cuts a circular disc slightly over two inches in diameter. Four discs will usually weigh about two grams. When sampling yarn, form sample into small coil. Hold in place by tying with one of the ends.

3.6.3.4 *Procedure*

1. Dry the glass weighing bottle at 221-230°F (105-110°C) to constant weight. Place the weighing bottle and cover separately in the oven. After heating for 1 hour, replace the cover, transfer the weighing bottle to the desiccator and allow it to cool to room temperature. Remove the cover momentarily to equalize the pressure, and with the cover in place, weigh the container. Repeat the heating, cooling, and weighing until the weight of the empty weighing bottle is constant to within ± 0.001 g.
2. Place the specimen to be tested in the container, cover, and weigh. Subtract the weight of the empty container (1.) from this weight to obtain the air-dry weight of the specimen, weight A.
3. Place the uncovered weighing bottle and specimen in the oven for 1 1/2 hours at a temperature of 221-230°F (105-110°C). Cover and transfer the container to a desiccator. When the container has cooled to room temperature, remove the cover momentarily to adjust the pressure, replace the cover, and weigh. Repeat the heating for periods of not less than 20 minutes, cooling and weighing until the weight is constant to within ± 0.001 g. Subtract the weight of the empty container from this weight to obtain the oven-dry weight of the specimen, weight B. When textiles are

heated under the conditions described, volatile materials, in addition to moisture, may be removed. If this possibility is known or suspected, it should be reported that the percentage loss in weight of the textile does or may include volatile substances as well as moisture.

3.6.3.5 Calculations

Calculate the moisture content of the specimen as follows:

$$\text{Moisture content, percent} = \frac{A-B}{A} \times 100 \quad 3.6.3.5(a)$$

Calculate the moisture regain of the specimen as follows:

$$\text{Moisture regain, percent} = \frac{A-B}{B} \times 100 \quad 3.6.3.5(b)$$

where:

A = air-dry weight of the specimen

B = Oven-dry weight of the specimen

3.6.4 Determination of fiber diameter

3.6.4.1 Description and application

This method describes a procedure for determining the average diameter of fibers by means of a microscope fitted with an image splitting eyepiece. This instrument measures the distance across an object as it lays upon a glass slide. Therefore, this is a valid diameter measurement only if the fibers are essentially true cylinders. Since different types of fibers have characteristic shapes it is possible to use this procedure for irregularly shaped fibers by determining an area factor for the particular type of fiber being measured by means of microphotography.

Figure 3.6.4.1 is a sketch showing the optical scheme incorporated in the instrument. In the Image Splitter a prism system is interposed between microscope objective and eyepiece to produce a double image of the microscope field of view. This prism system is precisely rotatable by a micrometer screw. Upon rotation of the prisms double images of objects in the field of view transverse one another. Measurement is accomplished by reading off the micrometer the amount of prism rotation required to place on object's double images exactly edge to edge in the axis of desired measurement. Measurement is accomplished in the plane of the object.

The accuracy which can be obtained and the size limits for various conventional microscope objectives are shown in Table 3.6.4.1.

3.6.4.2 Apparatus

The following equipment is needed for this procedure:

1. Microscope, Unitron monocular model MLU with 5X, 10X, 20X and 40X objectives, fitted with a Vickers AEI 10X image splitting eyepiece, or equivalent.
2. Microscope lamp, A.O. Spencer, Fisher Catalog #12-394, or equivalent.
3. Glass microscope slides (e.g., Fisher Catalog No. 12-550).
4. Sharp knife or razor blade for cutting sample.

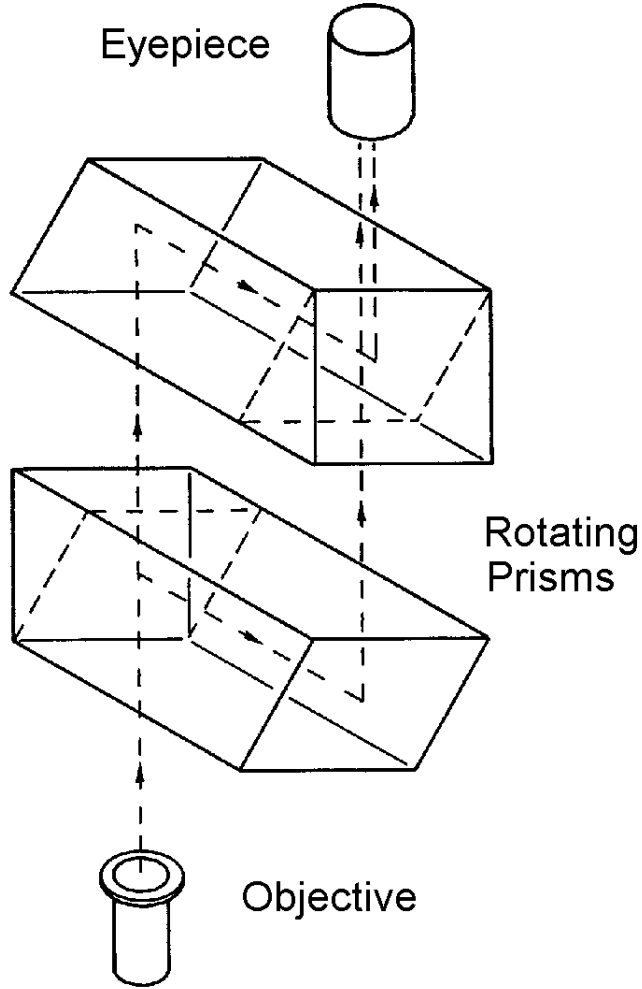


FIGURE 3.6.4.1 Schematic diagram of the optics of an image-splitting microscope.

TABLE 3.6.4.1 Accuracy and size limits.

OBJECTIVE POWER		READING ACCURACY		MAXIMUM SIZE OBJECT WHICH CAN BE COMPLETELY SHEARED	
5X	(N.A. 0.15)	0.00008"	2.0 μ m	0.04"	1.0 mm
10X	(N.A. 0.28)	0.00004"	1.0 μ m	0.02"	0.5 mm
20X	(N.A. 0.50)	0.000026"	0.6 μ m	0.01"	0.25 mm
40X	(N.A. 0.65)	0.0000128"	0.325 μ m	0.005"	0.12 mm

3.6.4.3 Calibration

Assemble and calibrate the microscope following the directions supplied with the instrument. If for any reason a different eyepiece or objective is used, the instrument must be recalibrated for the new part.

3.6.4.4 Prepare slide

Select representative strands from the sample and align in an even bundle. Place the bundle on a spare glass slide and hold it in place with the top of the finger. Cut the strands with a sharp instrument to secure smooth even ends. Place the strands on a clean slide so that the even ends are near one edge of the slide. (See Figure 3.6.4.4.) Cut the strands so that the pieces approximately .19 in. (0.5 mm) will be produced. The pieces will dust in a fine spray over the surface of the slide in an even pattern.

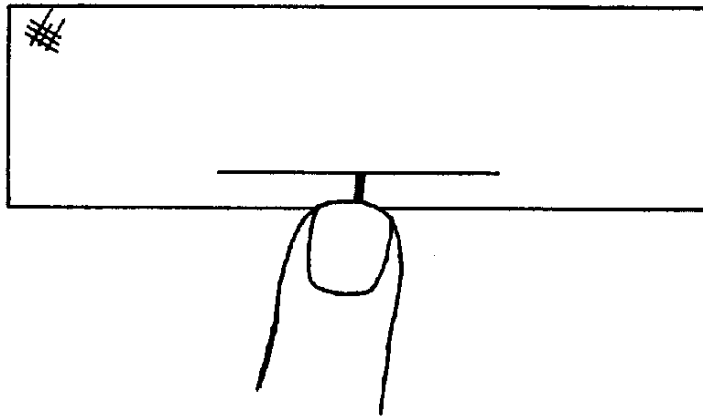


FIGURE 3.6.4.4 *Place the strands on a clean slide so that the even ends are near one edge of the slide.*

3.6.4.5 Measuring procedure

1. Place the slide under the microscope and select at random a single fiber. The fiber will appear as parallel red and green lines.
2. Rotate the image splitter until the fiber is parallel with the axis of the micrometer barrel and the ends of the two image are even.
3. Bring into sharp focus. Rotate the micrometer until the red and green images overlap forming a single black line. Continue the rotation until the red and green lines again separate and a band of light shows between them. Reverse the rotation and slowly bring the colored images back together until they just touch. Neither a thin light nor black line should be visible. Record the micrometer reading. If the micrometer should be turned too far so that the black line appears back off and start over. This will eliminate the effect of any backlash in the mechanism.
4. Continue to rotate the micrometer until the images have completely overlapped and are just ready to separate on the opposite side. Turn the micrometer very slowly until the thick black line completely disappears. At this point the red and green images should be just touching with no light

showing between them. Record the micrometer reading. The difference between the two readings is equal to twice the width of the object being measured.

5. Select other fibers and continue the measurements until twenty pieces have been measured. Move the slide in a uniform pattern to eliminate the possibility of measuring the same piece twice.

3.6.4.6 Calculation

List the difference in micrometer readings obtained in Paragraph 5 for each of the twenty measurements. Divide this number by two then multiply the result by the calibration factor for the microscope to obtain diameter measurement in microns. Calculate the average for the twenty measurements.

If the diameter measurement calculated above is to be used to calculate cross sectional area for strength determinations see Section 3.6.4.1. For example, the area of Thornel 25™ fibers may be calculated as follows: calculate the area using the average diameter determined in this procedure. Multiply this area by the area factor to obtain the actual area. (An area factor of 0.66 has been determined for Thornel 25™.)

3.6.5 Determination of electrical resistivity

3.6.5.1 Scope

This method describes a procedure for determining the electrical resistance of carbon and graphite cloth and felt. It is used as a control measure for checking temperature of processing and to determine compliance of materials with specific resistance specifications.

3.6.5.2 Apparatus

The following equipment is needed for this procedure:

1. Jig for clamping cloth.
2. Vacuum tube volt-ohmmeter. Triplet #850 or equivalent.
3. Scissors or other implement for cutting samples.

3.6.5.3 Sample preparation

For cloth, obtain a 1/2 yard long (45.7 cm), full width piece of each roll of cloth to be tested. Cut five warp and five fill direction strips 1-1/4" wide and 11" to 12" (27.9 to 30.5 cm) long. Distribute the location of the strips over the entire area of the cloth sample. Ravel each strip to the nearest thread to one inch width. For felt samples, obtain a 1/2 yard long (45.7 cm), full width piece of each roll of felt to be tested. Cut five strips in "warp" direction and five strips in "fill" direction using a 1" x 12" (25 mm x 305 mm) metal template. Distribute the location of strips over the entire area of the felt sample.

3.6.5.4 Procedure

1. Adjust the silver jaws of the resistance jig to provide a test length of 10".
2. Clamp sample in jig and measure resistance.

3.6.5.5 Calculation

Divide observed resistance by 10 to obtain ohms/square value. (See Section 3.6.5.7.) Determine the average resistance for five strips and record on data sheet as ohms per inch per inch width.

3.6.5.6 Calibration and maintenance

Vacuum tube volt-ohmmeters are used for fabric and felt measurement. The meter and jig should be calibrated every six months with a standard resistance box, certified to NBS standards. Any incident requiring meter maintenance (tube replacement, etc.) should be followed by recalibration regardless of the six month routine check.

The zero and full scale adjustment should be checked each shift the meter is used. If meter fails to adjust properly to zero and full scale, it must be checked by the electrical maintenance department. The zero adjustment compensates for lead wire and meter resistance errors.

3.6.5.7 Definition of units of measurement

The electrical resistance measurement on cloth and felt is expressed in ohms per square (unit area). This is not the same value as the specific resistance measured on bulk carbon. The fabric resistance value is proportional to specific resistance when a given grade is considered. For example, carbon cloth has higher resistance than graphite cloth, the same material after graphitization.

The size of the square (unit area) does not influence the resistance value of the cloth or felt. This can be demonstrated with the standard equation for the relation between sample resistance and specific resistance for a solid rectangular shape.

$$P = \frac{RTW}{L} \text{ or } R = \frac{PL}{TW} \quad 3.6.5.7(a)$$

where

- P = specific resistance
- R = sample resistance
- L = sample length
- T = sample thickness
- W = sample width

For materials with identical specific resistance (P) such as copper, the resistance of one square inch of a given thickness would be:

$$R = \frac{PL}{TW} = \frac{P}{T} \cdot \frac{1}{1} \quad 3.6.5.7(b)$$

Since T and P are constant, the resistance of the one inch square can be written:

$$R = K \frac{L}{W} = K \frac{1}{1} = K \quad 3.6.5.7(c)$$

If the square is made twice as large (2 x 2), the resistance of the square will remain the same.

$$R = K \frac{L}{W} = K \frac{2}{2} = K \quad 3.5.6.7(d)$$

Therefore, the resistance of fabrics is reported as ohms/square. The user can use any unit for the square he chooses, inch, centimeter, foot or yard.

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