NASA Technical Memorandum 108495

Composite Processing Development to Improve Interlaminar Strength Using Ply Interface Particles (Center Director's Discretionary Fund Final Report No. 93-13)

A.T. Nettles

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I. INTRODUCTION

Interlaminar shear strength is the Achilles heel of laminated composites. The ease with which the laminae (or layers) come apart or deply is of great concern, especially in instances of foreign object impact damage. Of the two major types of matrix damage to composites (matrix cracking and delamination), delamination poses the most serious threats to the structural integrity of hardware made from laminated polymer matrix composites. The plies can be better held together by methods such as stitching or braiding the fibers together before matrix resin impregnation, but this sacrifices many other properties such as tensile strength and modulus. The goal is to not disturb the continuous reinforcement fibers while making the plies hold together better (more commonly called "through-the-thickness" or "z-direction" strengthening). If this is to be done without extremely elaborate processing techniques, commercially available prepreg material should be used to make a composite laminate. Thus, a method of modifying the prepreg laminate before or during cure would be desirable.

Evans and Boyce[1] introduced two methods of inserting reinforcement in the z-direction of uncured laminates. One method inserts yarns in an uncured laminate via an ultrasonic horn with a hollow tip, and the other method inserts large fibers into the laminate during cure via a collapsible foam. It is claimed that 0° laminates suffer about an 8-percent drop in compression strength and cross-ply laminates lose only 2 percent of their tensile strength. The ±45° intralaminar shear strength increased 7 percent, and the main effect of the z-direction reinforcements, the interlaminar strain energy release rate, increased in mode I (peeling) by 250 percent. Qualitative results are given that show that the damage area of impacted laminates significantly decreased when the z-direction fibers were in place.

A group of researchers in Japan[2] added nickel-coated silicon-carbide (Si-C) whiskers to unidirectional prepreg and then used a magnetic field to align them in the z-direction during cure. Results show that the average mode I (peeling) strain energy release rate of the z-direction reinforced laminates was about twice that of samples with no z-direction reinforcement. The specimens with the whiskers demonstrated a large variation (scatter) in the results for these tests. End notched flexural- and short-beam shear tests indicated that the z-direction reinforcements had no effect on the mode II (shear) interlaminar strain energy release rate or interlaminar shear strength. This study also showed that there was a critical whisker volume that maximized the mode I strain energy release rate (approximately 10-percent whiskers to continuous carbon fiber reinforcement). The degradation of in-plane properties was not given.

II. MECHANICS OF SHEAR

A. Description of Shear in Laminates

1. Interlaminar Versus Intralaminar Shear. It is worth mentioning the differences between interlaminar shear and intralaminar shear and what causes each since the two are so often misunderstood.

a. Interlaminar shear. Inter is a prefix meaning between. Thus, interlaminar shear strength is the strength with which the plies adhere to each other only in the region between the plies. This shear strength is usually not very strong in laminated composites because no reinforcements run between the plies to help hold them together. Only the relatively weak matrix resin is present to carry the shear stresses in this region.

There are three types of shear stresses that can act to separate one ply from another. These are mode I (peeling), mode II (pure shear), and mode III (tearing). These three types of stresses are shown schematically in figure 1.

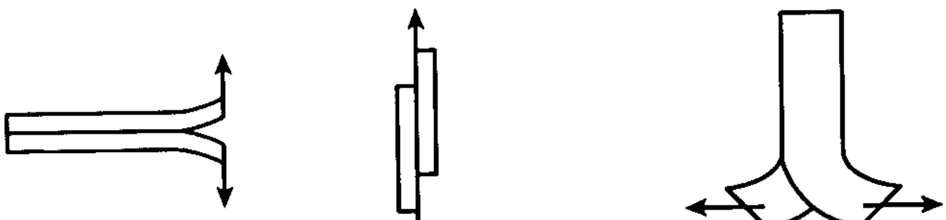

Figure 1. The three types of shearing modes.

For laminated composite materials, mode II (pure shear) is of the most interest since bending stresses in a laminated plate will give rise to mode II shear stresses that tend to cause delaminations. Foreign object impact is notorious for causing delaminations in laminated composites due to the high mode II shear stresses set up in the material. A method to inhibit these delaminations from forming was the aim of this project. Figure 2 is a schematic of the formation of a delamination due to foreign object impact.

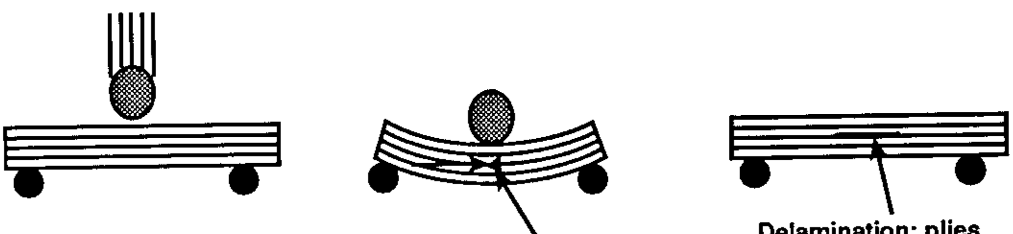

Figure 2. Development of a delamination by impact damage.

After formation of a delamination, it can grow in mode I peeling if the specimen is put under a compressive stress, or it can further grow by mode II if the specimen experiences additional bending. Some mode III tearing may also be present, although its contribution is usually very small.

b. Intralaminar shear. Intra is a prefix that means within. Thus, intralaminar shear is the shear stress induced within each individual ply of the laminate, and not the shear stresses between the plies. Intralaminar shear stresses are induced into the laminate by in-plane stresses and strains. Note that in the discussion on interlaminar shear stresses, these stresses were induced by an out-of-plane load such as three-point bending. For unsymmetrical layup configurations, it is possible to induce bending strains into the laminate by applying an in-plane tensile load, but in practice these types of layups are rare and transverse impact loading is still a more severe threat for delaminations.

Other than applying an in-plane shear load to a unidirectional laminated plate, the best method to induce maximum shear stresses parallel and perpendicular to the fibers (principal material directions) within the plies of a laminate is to perform a 45° tensile test. If a load is applied to a ply that contains fibers that are aligned at a 45° angle to the load, then in-plane shear stresses will be maximized in the principal material directions. This will be discussed in a later section.

c. Intuitive Difference in Intra and Interlaminar Shear Strength. An easy method to visualize the difference in the intralaminar and interlaminar shear strengths is to visualize a laminate that has not been consolidated and the plies are not bonded together at all. If a beam is cut from this laminate and subjected to a three-point bend, the deflections will be very large due to the layers sliding across one another. If a tensile specimen is cut from this laminate, there will not be a drastic difference in deformation due to the applied load.

B. Analysis of Shear in Laminates

1. Intralaminar Shear. It is now convenient to put the strain/stress relationships into equation form. The total relationship in matrix form is:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix} = \begin{bmatrix} \overline{S_{11}} & \overline{S_{12}} & \overline{S_{16}} \\ \overline{S_{12}} & \overline{S_{22}} & \overline{S_{26}} \\ \overline{S_{16}} & \overline{S_{26}} & \overline{S_{66}} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} \quad , \tag{1}$$

where,

$$\begin{aligned}
\overline{S_{11}} &= S_{11}\cos^4\theta + (2S_{12}+S_{66})\cos^2\theta\sin^2\theta + S_{22}\sin^4\theta \quad , \\
\overline{S_{12}} &= (S_{11}+S_{22}-S_{66})\cos^2\theta\sin^2\theta + S_{12}(\cos^4\theta\sin^4\theta) \quad , \\
\overline{S_{22}} &= S_{11}\sin^4\theta + (2S_{12}+S_{66})\cos^2\theta\sin^2\theta + S_{22}\cos^4\theta \quad , \\
\overline{S_{16}} &= (2S_{11}-2S_{12}-S_{66})\cos^3\theta\sin\theta + (2S_{12}-2S_{22}+S_{66})\cos\theta\sin^3\theta \quad , \\
\overline{S_{26}} &= (2S_{11}-2S_{12}-S_{66})\cos\theta\sin^3\theta + (2S_{12}-2S_{22}+S_{66})\cos^3\theta\sin\theta \quad , \\
\overline{S_{66}} &= (2S_{11}+2S_{22}-4S_{12}-S_{66})\cos^2\theta\sin^2\theta + S_{66}/2\,(\cos^4+\theta\sin^4\theta) \quad ,
\end{aligned} \tag{2}$$

and the S_{ij} are determined from the lamina engineering constants as:

$$S_{11} = \frac{1}{E_1} , \qquad S_{22} = \frac{1}{E_2} ,$$
$$S_{12} = \frac{-\nu_{12}}{E_1} , \qquad S_{66} = \frac{1}{G_{12}} . \tag{3}$$

Referring back to equation (1) and applying only a tensile load in the x-direction, the strain/stress relationship for a lamina becomes:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix} = \begin{bmatrix} \overline{S_{11}} & \overline{S_{12}} & \overline{S_{16}} \\ \overline{S_{12}} & \overline{S_{22}} & \overline{S_{26}} \\ \overline{S_{16}} & \overline{S_{26}} & \overline{S_{66}} \end{bmatrix} \begin{bmatrix} \sigma_x \\ 0 \\ 0 \end{bmatrix} . \tag{4}$$

Thus,

$$\varepsilon_{xy} = \overline{S_{16}} \sigma_x , \tag{5}$$

and if θ is not either 0° or 90°, then the x-direction tensile stress will cause an x-y plane shear strain. In order to maximize this x-y shear strain, $\overline{S_{16}}$ must be maximized. From equation (2):

$$\overline{S_{16}} = (2S_{11} - 2S_{12} - S_{66}) \cos^3 \theta \sin \theta + (2S_{12} - 2S_{22} + S_{66}) \cos \theta \sin^3 \theta ,$$

which will be maximized when $\frac{\partial \overline{S_{16}}}{\partial \theta} = 0$, which occurs at $\theta = \pm 45°$.

All of the above analysis is based on the assumption of constant stress being applied across the specimen's edges. As was shown, this type of applied stress will result in a shear strain (given by equation (5)). Figure 3 shows the deformation that a 45° ply will assume given this uniform stress.

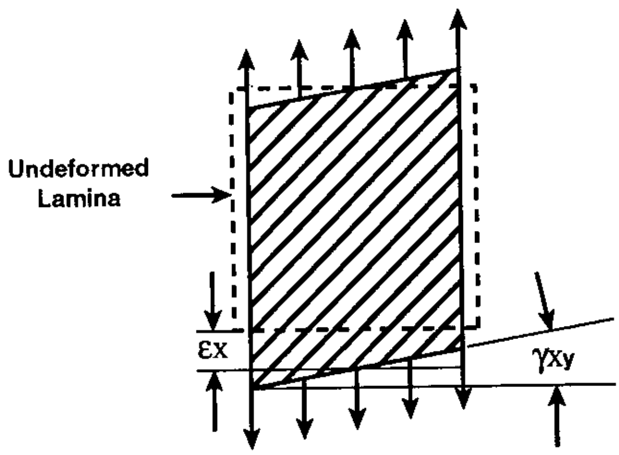

Figure 3. Deformation of a 45° lamina subject to uniform stress.

In actuality, the strain is uniform across the loading edges since the specimen is clamped at these boundaries. The stress/strain relationship is given by:

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}} \\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}} \\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \quad , \tag{6}$$

where,

$$\begin{aligned}
\overline{Q_{11}} &= Q_{11}\cos^4\theta + 2(Q_{12}+2Q_{66})\cos^2\theta\sin^2\theta + Q_{22}\sin^4\theta \quad , \\
\overline{Q_{12}} &= (Q_{11}+Q_{22}-4Q_{66})\cos^2\theta\sin^2\theta + Q_{12}(\cos^4\theta + \sin^4\theta) \quad , \\
\overline{Q_{22}} &= Q_{11}\sin^4\theta + 2(Q_{12}+2Q_{66})\cos^2\theta\sin^2\theta + Q_{22}\cos^4\theta \quad , \\
\overline{Q_{16}} &= (Q_{11}-Q_{12}-2Q_{66})\cos^3\theta\sin\theta + (Q_{12}-Q_{22}+2Q_{66})\cos\theta\sin^3\theta \quad , \\
\overline{Q_{26}} &= (Q_{11}-Q_{12}-2Q_{66})\cos\theta\sin^3\theta + (Q_{12}-Q_{22}+2Q_{66})\cos^3\theta\sin\theta \quad , \\
\overline{Q_{66}} &= (Q_{11}+Q_{22}-2Q_{12}-2Q_{66})\cos^2\theta\sin^2\theta + Q_{66}(\cos^4\theta + \sin^4\theta) \quad ,
\end{aligned} \tag{7}$$

and the Q_{ij} are determined from the lamina engineering constants as:

$$Q_{11} = \frac{E_1}{1-\nu_{12}\nu_{21}} \quad , \qquad Q_{22} = \frac{E_2}{1-\nu_{12}\nu_{21}} \quad ,$$
$$Q_{12} = \frac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}} \quad , \qquad Q_{66} = G_{12} \quad . \tag{8}$$

Thus, for a uniform strain applied in the x-direction, equation (6) becomes:

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}} \\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}} \\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ 0 \\ 0 \end{bmatrix} \quad , \tag{9}$$

which, for shear stress, reduces to:

$$\tau_{xy} = \overline{Q_{16}}\varepsilon_x \quad , \tag{10}$$

where (from equation (7)),

$$\overline{Q_{16}} = (Q_{11}-Q_{12}-2Q_{66})\cos^3\theta\sin\theta + (Q_{12}-Q_{22}+2Q_{66})\cos\theta\sin^3\theta \quad ,$$

which is a maximum at $\theta = 45°$. Thus to induce the maximum amount of shear stress into a lamina by applying only a uniform tensile strain, the fibers should be at 45° to the direction of pull. This is why a tensile coupon is pulled at 45° and –45° to the fibers in order to find a lamina's in-plane shear strength (both +45° and –45° plies must be included to give a symmetric laminate).

But for the interest of the research being performed on this project, the shear strength between plies is the critical parameter. The question remains as to what happens between plies during a ±45° tensile test.

2. Interlaminar Effects of the ±45° Tensile Test. Whatever interlaminar strains that occur in a ±45° tensile specimen are due to the "scissoring" effects between plies. This can be best demonstrated using a square "specimen" as depicted in figure 4.

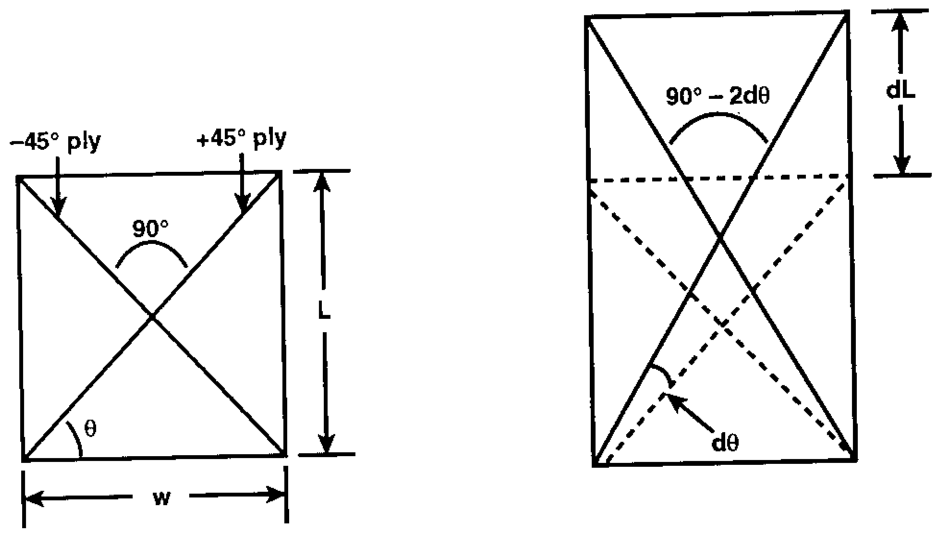

Figure 4. "Scissoring" effect on a tensile specimen.

From the figure, the following relationship between the specimen's length, width, and diagonal angle θ is:

$$\tan \theta = \frac{L}{w} \qquad \text{or} \qquad \theta = \tan^{-1}\left(\frac{L}{w}\right) \ . \tag{11}$$

Therefore,

$$d\theta = \frac{1}{1+\left(\frac{L}{w}\right)^2}\left(\frac{1}{w}\right) dL = \frac{dL}{w+\frac{L^2}{w}} \ . \tag{12}$$

The tensile direction strain is defined as dL/L and the shear strain is $2d\theta$. Therefore, the shear strain can be related to the tensile strain by using the fact that $dL = \varepsilon_x L$ and $\gamma_{xy} = 2d\theta$. The result is:

$$\gamma_{xy} = \frac{2wL}{w^2+L^2}\,\varepsilon_x \ . \tag{13}$$

For the specimens used in this study, w = 1 inch and L = 7 inches, therefore,

$$\gamma_{xy} = \frac{2(7)}{(1)+(49)} \varepsilon_x = 0.28\ \varepsilon_x \quad . \tag{14}$$

The typical failure strain for a ±45° tensile specimen is about 1-percent strain so the interlaminar shear strain at this point is about 0.28-percent strain. This will be compared to the short-beam shear failure strain obtained in the next section.

3. Mechanics of the Short-Beam Shear Test. The most common, and by far the easiest, method to induce high interlaminar shear stresses between plies is to subject a relatively thick beam to a three-point bend. By shortening up the span length of the beam, the axial stresses are minimized (i.e., the bending moment is minimized) compared to the shearing stress, which is constant for a given load regardless of span length. Since the external axial stresses are zero at the center of the beam and a maximum at the top and bottom surfaces, it is desirable to have these planes sufficiently far apart so that only pure shear (which is a maximum at the center) acts through the center of the beam; thus, the relative thickness (width to depth ratio of one or less) of the specimens.

If a laminate does not have its plies bonded together, a three-point bend would cause the laminate to deform as in figure 5.

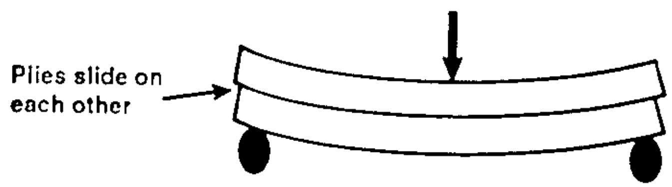

Figure 5. A two-ply laminate with unbonded layers during bending.

If this were to occur, then all of the laminate's flexural rigidity would be lost. This sliding or shearing motion is suppressed by the bond between the plies of a laminate. Once this bond is broken, a sharp reduction in load is seen even though the specimen can (and will) still carry a load.

a. Interlaminar shear strain. By classical beam theory, the maximum shear stress and strain occurs at the center of the beam and is given by:

$$\tau_{max} = \frac{3F}{2wt} \quad , \tag{15}$$

and,

$$\gamma_{max} = \frac{\tau_{max}}{G} \quad , \tag{16}$$

where F is the applied load at the center of the beam, w is the beam width, t is the beam thickness, and G is the shear modulus of the resin. In most cases, the resin shear modulus is approximately on the order of 1×10^6 lb/in^2 and the ultimate shear stress is in the vicinity of 10,000 lb/in^2 which indicates that near failure in the interlaminar shear strain is about 1 percent. This is about four times higher than the interlaminar shear strain that was obtained from the ±45° tensile test. This is why a ±45° tensile test is not used to measure interlaminar shear strength. Specimens with a w/L ratio of one can be used, but a large enough gauge section cannot be achieved for practical testing purposes.

C. Improving Interlaminar Strength

1. Interlaminar Reinforcement. By placing reinforcements between plies, the reinforcements can share carrying the mode II shear loads, thus allowing a higher shear stress to develop before the plies break apart. Imagine figure 5 being two wooden planks lying atop one another. The sliding between the two can be suppressed by gluing the planks together (an adhesive bond) or by nailing the planks together (a "through-the-thickness" reinforcement bond). In the case of laminated polymer matrix composites, the "gluing" method alone will give a much weaker bond than "gluing" and using "through-the-thickness" reinforcements.

III. APPROACH

A. Problems With the Approach

1. Catalyst for Research. This work was inspired by preliminary results from a study at Auburn University in which short nickel fibers were mixed into the matrix resin of carbon, Kevlar™, and Spectra™ fiber unidirectional composite samples. In this study (which has not been fully documented), the mode II strain energy release rate was reported to be increased twofold by the addition of 10 percent by weight nickel fibers. End notched flexural specimens were used and no interlaminar strength data was measured.

2. Initial Errors in the Study. Two fatal flaws were present in the study at the time the author joined the project. First, the ±45° tensile test was being used to examine interlaminar shear strength. This test measures intralaminar shear strength which has no bearing on this project. Secondly, load/strain data were being taken using a PC-based data acquisition system, and, during the testing, wrong parameters were entered into the system for two of the families of tests, resulting in the strain readings being half of what they actually were. This was not discovered until the author examined a plot of the data in which the mistake is blatantly obvious. Unfortunately, results from these tests were used to proceed with further testing since the results seemed encouraging.

B. Experimental

1. Transverse Reinforcement. In this research study, aluminum "whiskers" were placed between plies of commercially available prepreg in an attempt to increase the interlaminar strength of the laminate. All of the laminates used in this study were of a cross-ply stacking sequence. The amount of aluminum placed between plies was varied from 0.0001 to 0.01 g/cm^2 for the ±45° tensile specimens and 0.0001 to 0.0005 g/cm^2 for the short-beam shear samples to see if this had any effect on the measured interlaminar shear strength. Side and planar views of the specimens with 0.0001, 0.002, 0.005, and 0.01 g/cm^2 of aluminum particles are shown in the appendix.

As can be seen from the photographs, the particle areal densities of 0.005 and 0.01 g/cm^2 completely separated the laminae within the laminate. From the planar views, it can be seen that the resin did not wet out through the "web" of particles that was created, thus causing the laminate to be delaminated after processing. This was confirmed by bending tests in which a beam of the aluminum-modified laminate could easily be deplied by hand, an occurrence that should never take place within a laminated composite.

Another variable examined was the size of the aluminum "whiskers." This parameter was controlled by sifting the aluminum through sieves of different mesh sizes, proceeding from an initially course mesh to a finer and finer one to obtain approximately four different families of lengths of the aluminum whiskers. The four mesh sizes used were 80, 150, 250, and 400 openings per inch.

In addition to the aluminum particles, Si-C whiskers were also examined as a translaminar reinforcement. These particles were applied between prepreg laminae by spraying an emulsion of deionized water and Si-C particles directly onto the prepreg surface and allowing the water to fully evaporate. Difficulty in preventing the Si-C whiskers from clumping was helped somewhat by controlling the mist of the emulsion spray.

IV. RESULTS

1. <u>±45° Tensile Testing</u>. As mentioned in section III, these tests had little bearing on the ultimate goal of this project. Nevertheless, the results obtained are included here for completeness. Load/strain data for specimens with 0.0001, 0.002, 0.005, and 0.01 g/cm^2 of aluminum particles between each ply is plotted in figure 6. These specimens contained aluminum particles of various sizes (i.e., the sieves were not used).

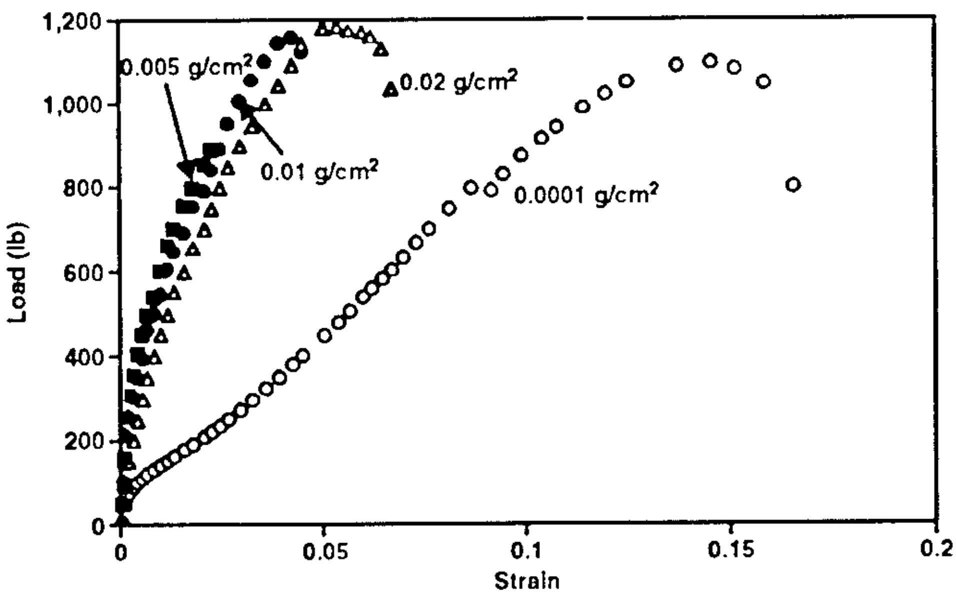

Figure 6. Plot of load/strain data for ±45° tensile tests.

As can be seen, the behavior of the samples containing 0.0001 g/cm^2 of aluminum per ply is drastically different than the other three samples tested. In fact, the modulus is exactly one-half that of the others and its ultimate strain to failure is also twice as large. The only explanation is that the data acquisition was incorrectly taken and the strain measurements were off by a factor of two. Initial conclusions were that the additional aluminum particles in the other three samples (which contained much more aluminum) contributed to a stiffer specimen. In order for this to be true, a sudden jump, or singularity, in the data must exist at some point between 0.0001 and 0.002 g/cm^2 of aluminum particles per ply. There is no physical or mathematical basis for such a singularity to exist and the data should have been rejected at this point.

2. Short-Beam Shear. In an effort to assess the true interlaminar shear strength of the laminates constructed with ply particles, the short-beam shear test was suggested for use by the author. In addition, only specimens with 0.0001 g/cm^2 of aluminum per ply were suggested for testing since the cured panels with 0.002 g/cm^2 or more of aluminum particles per ply would delaminate when bent by hand, an indication of a laminate with near zero interlaminar strength.

A total of 15 cross-ply specimens with and without the aluminum were tested. The specimens with aluminum were 6.9 mm (27 in) wide and 3.7 mm (0.15 in) thick and the ones without were 6.9 mm (0.27 in) wide and 3.3 mm (0.13 in) thick. The additional thickness is due to the aluminum particles between plies preventing complete consolidation and thus a slightly thicker specimen for a given number of plies. The average interlaminar shear strength for the specimens with and without aluminum particles was found to be 7,167±658 lb/in^2 and 13,025±917 lb/in^2, respectively. From these data it was obvious that the aluminum placed between prepreg plies during layup adversely affected the interlaminar shear strength of the composite.

3. Effect of Aluminum Size. The short-beam shear tests were conducted with particles of aluminum that were separated into four class sizes as mentioned earlier. There was no statistical difference between the data gathered for each of these four sizes of aluminum particles.

4. Si-C Whiskers. The short-beam shear test was performed to assess the effects of utilizing Si-C whiskers on the interlaminar shear strength of the composite. The material used in this portion of the study was IM7/977-2 with a bi-directional layup of 15 plies. The areal density of the applied Si-C was not measured since only a qualitative measurement was sought to assess the feasibility of continuing with this process. Thickness measurements showed that the Si-C specimens were about 0.005 in thicker than the control specimens with no Si-C, indicating that the Si-C may be preventing complete consolidation, much like the specimens with aluminum particles. The results showed that the specimens with aluminum carbide whiskers had an average strength of 14,417±521 lb/in^2 whereas the control specimens had an average strength of 14,181±1,007 lb/in^2.

V. CONCLUSIONS

Although the principal investigator left the project and it was abandoned after the initial Si-C tests, some lessons were learned from the testing performed.

- Applying particles between plies of a prepreg material with no alignment process can weaken, but not strengthen, the interlaminar shear strength of a composite laminate.
- It was experimentally verified that the ±45° tensile test measures intralaminar shear strength and not interlaminar shear strength since the aluminum between plies had no adverse effect on these tests, although the plies were essentially separated.
- In an experiment in which one of the independent variables is being gradually increased or decreased, the response or dependent variable usually responds in the same manner with no singularities (although many exceptions do exist). If a singularity is measured, a plausible explanation must be given.

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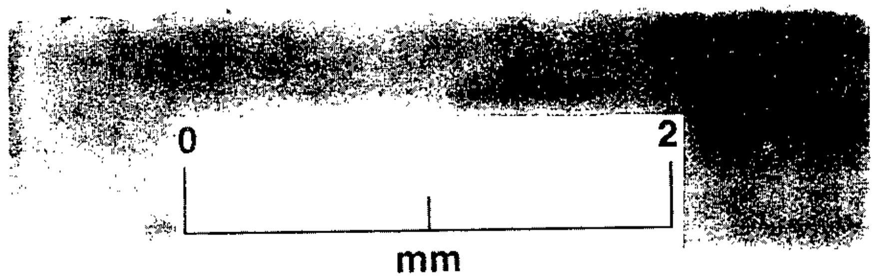
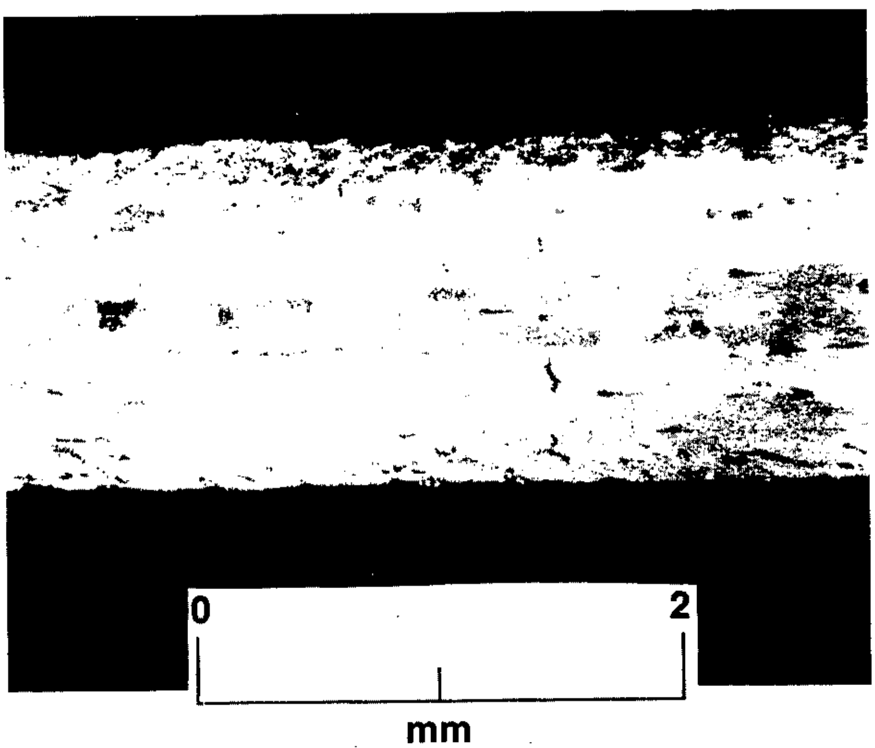
2. Yamashita, S., Hatta, H., Takei, T., and Sugano, T.: "Interlaminar Reinforcement of Laminated Composites by Addition of Oriented Whiskers in the Matrix." Journal of Composite Materials, vol. 26, No. 9, 1992, pp. 1254–1268.

APPENDIX

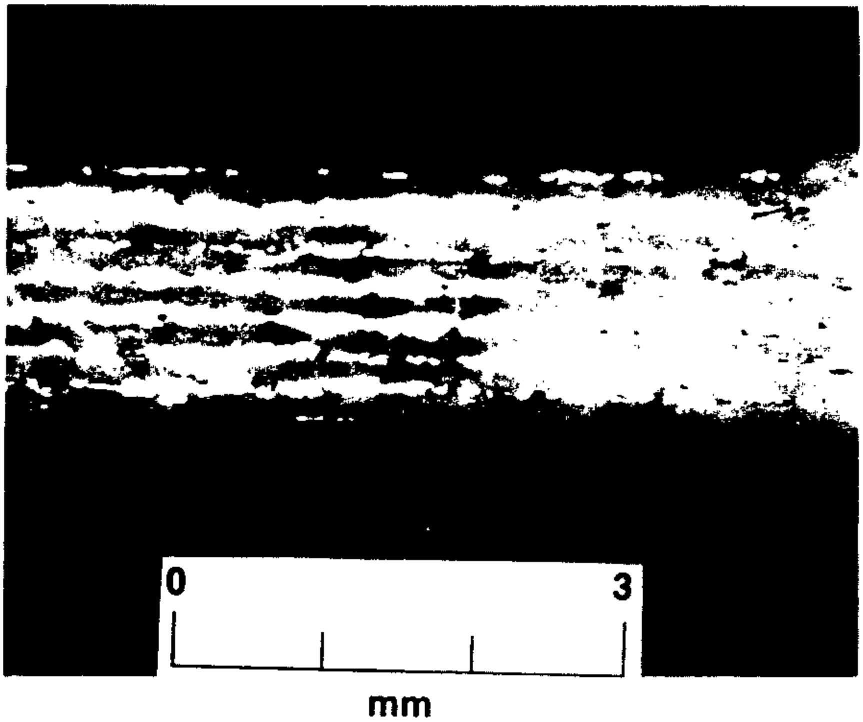
Photomicrographs of Specimens With Aluminum Particles



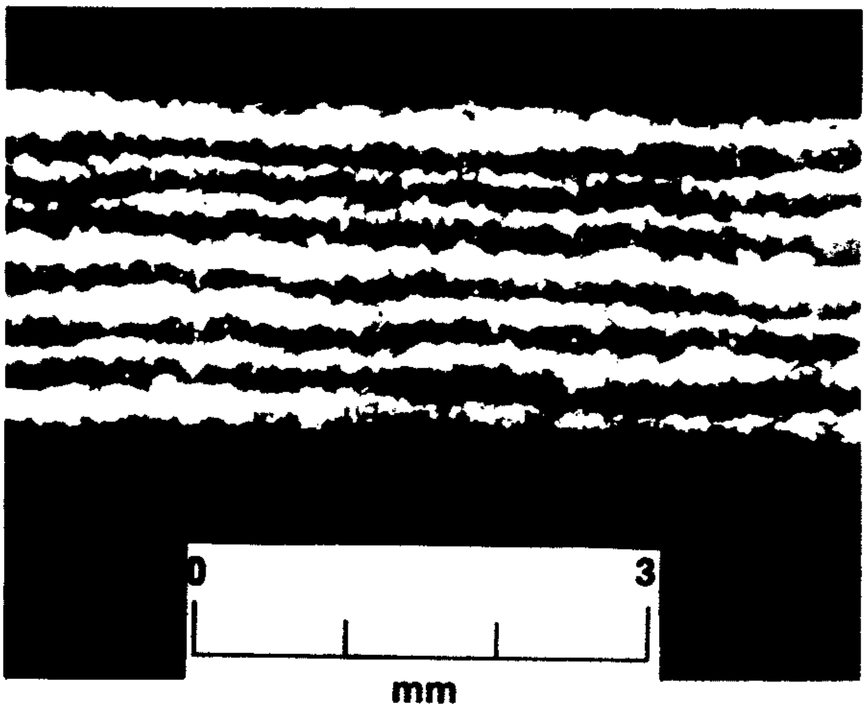
Side view of specimen with 0.0001 g/cm^2 of aluminum particles.



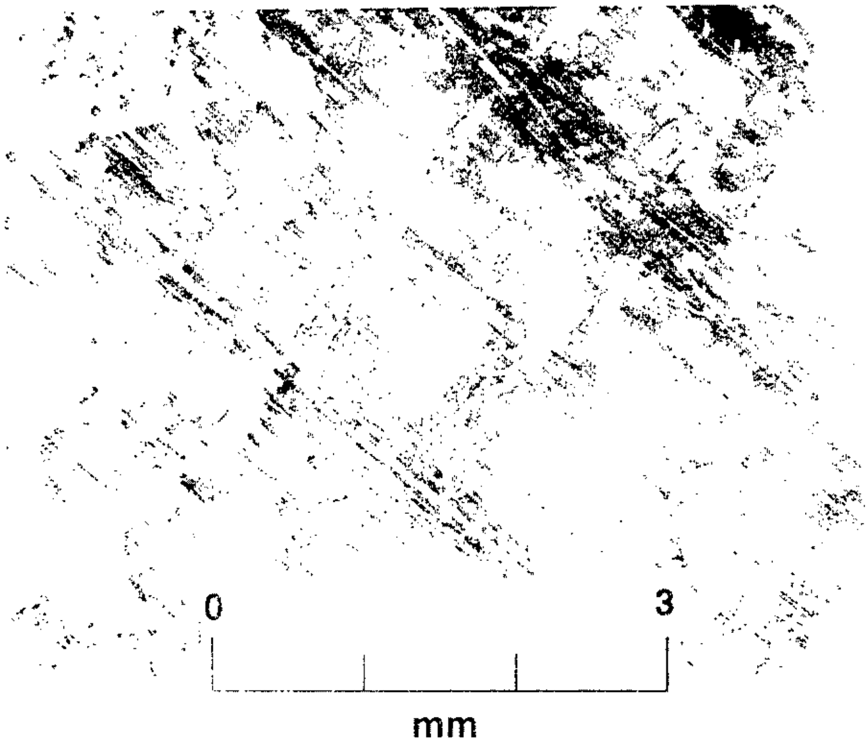
Side view of specimen with 0.002 g/cm^2 of aluminum particles.



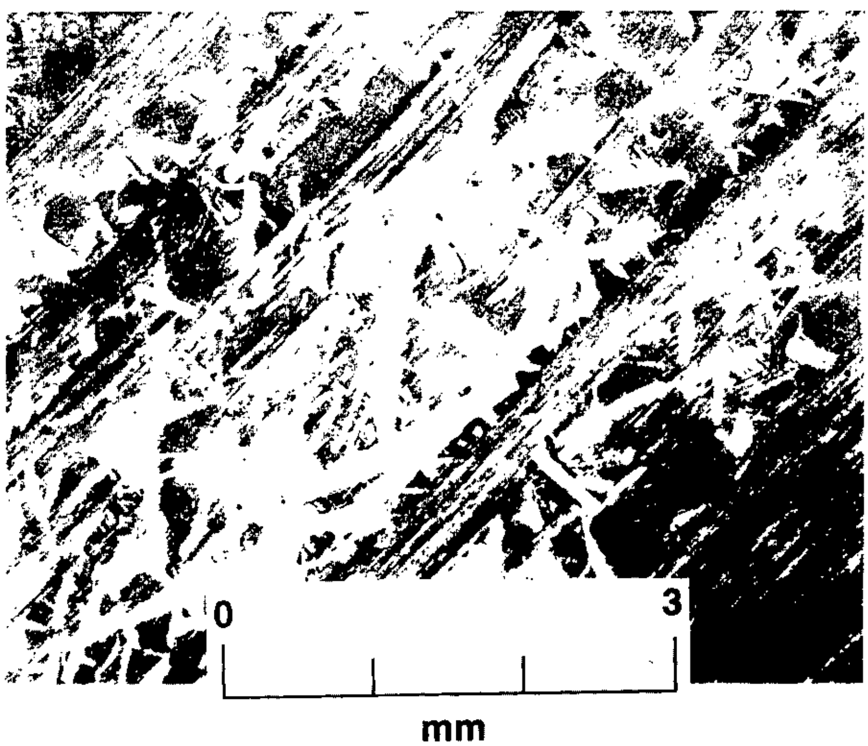
Side view of specimen with 0.002 g/cm^2 of aluminum particles.



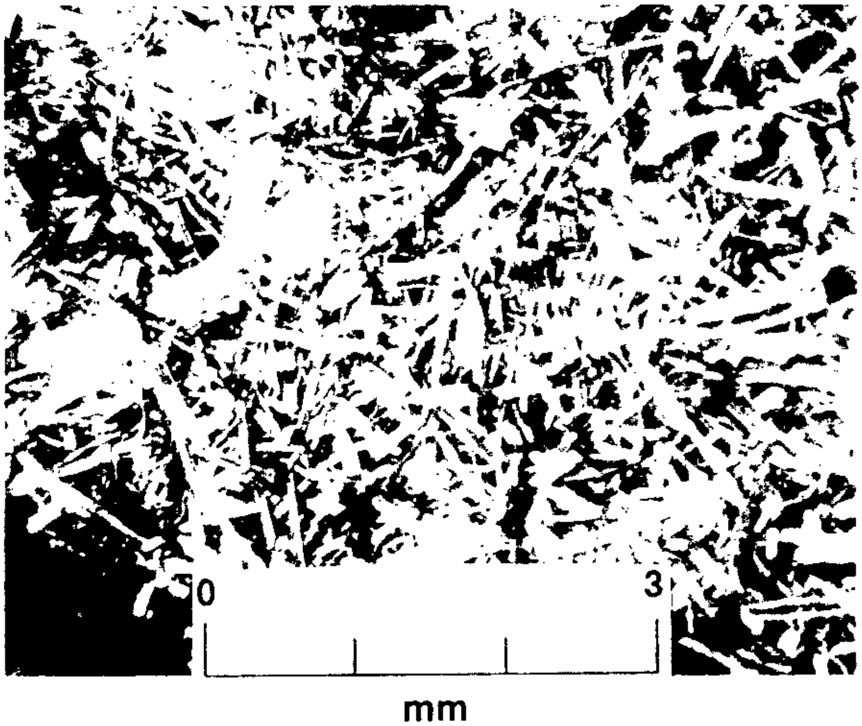
Side view of specimen with 0.01 g/cm^2 of aluminum particles.



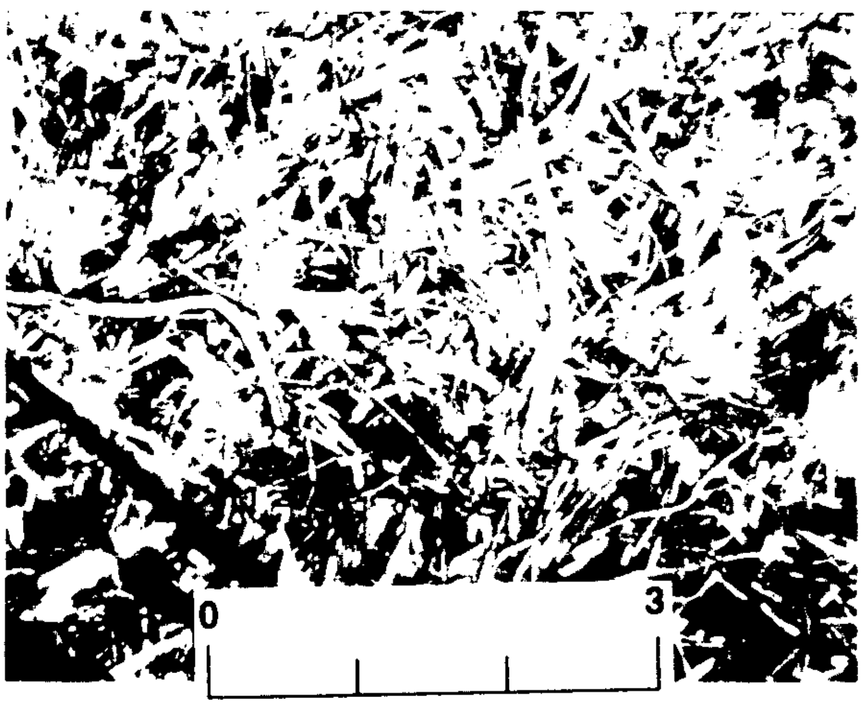
Planar view of specimen with 0.0001 g/cm^2 of aluminum particles.



Planar view of specimen with 0.002 g/cm^2 of aluminum particles.



Planar view of specimen with 0.005 g/cm^2 of aluminum particles.



Planar view of specimen with 0.01 g/cm^2 of aluminum particles.

APPROVAL

COMPOSITE PROCESSING DEVELOPMENT TO IMPROVE INTERLAMINAR STRENGTH USING PLY INTERFACE PARTICLES
MSFC Center Director's Discretionary Fund Final Report, Project No. 93-13

By A. Nettles

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

P.H. SCHUERER
Director, Materials and Processes Laboratory

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The interlaminar shear strength of carbon/epoxy laminates was to be improved by placing particles of aluminum between plies of prepreg tape used for the layup. Difficulty in aligning the aluminum whiskers in the transverse direction prevented any gain in strength. A discussion of shear within a laminate is presented to better understand the results.

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