MECHANICAL BEHAVIOR OF AN ALUMINA FIBER REINFORCED ALUMINUM WIRE IN TENSION AND AFTER AXIAL TORSION

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SUMMARY: The tensile behavior with and without preceding torsion of an aluminum/ 45vol% Nextel® 610 alumina fiber composite is investigated. For the undeformed wire the fracture strength varies between 1280 and 1400 MPa. From cyclic tension-tension tests a yield strength of the aluminum matrix of 25±5 MPa is calculated. Residual stresses in the matrix are in general tensile, ranging with some variability from 0 to 10 MPa. Twisting the wire results in a shortening of the wire and in a decrease in its fracture strength. Twisting and subsequent untwisting back to the initial configuration removes the shortening and causes no significant change in the wire fracture strength. The shortening and the decrease in fracture strength of the pre-twisted material is reasonably well predicted by analysis incorporating the influence of internal stresses caused by the twisting operation.

KEYWORDS: metal matrix composites, alumina fibre, aluminum, tensile strength, yield, unloading, wire, torsion, Swift effect.

INTRODUCTION

Continuous fiber reinforced aluminum matrix composites have a significant engineering potential due to their outstanding combination of high stiffness, high strength, and low density. One particularly interesting attribute of these composites is that attractive longitudinal mechanical properties can be achieved with a matrix of high purity [1-4]. Hence, relatively high electrical conductivity, on the order of one-half that of pure aluminum, can also be attained by this class of composite materials, such that continuous wires of high-strength fiber reinforced aluminum are emerging as an attractive candidate material for electric power transmission.

Electric power transmission cables are typically produced by combining strands of pure aluminum with a central core of stronger material, conventionally of steel; in such cables, fiber reinforced pure aluminum represents an attractive replacement of the lower-conductivity and denser steel core. As the cable is produced, the assembled bundle of wires is collectively twisted around its axis, causing in turn a certain degree of individual twisting of each wire composing the cable. As a consequence, in addition to longitudinal properties of the wires, their behavior during, as well as after, torsion is of practical significance.

While longitudinal and transversal properties of fiber reinforced materials have been the subject of significant research to date, the torsion behavior of these materials is rarely investigated. Information concerning the influence of twisting on longitudinal properties of such composite wires is also scarce, and found mainly in two forms in the literature: (i) the body of work on off-axis properties of anisotropic materials reviewed for example in [5], and (ii) studies of the behavior of twisted yarn, ropes and cords in textile research [6-8].

The present work is a study of the tensile and torsion/tension behavior of a high-performance metal matrix composite wire produced by 3M Corporation (StPaul, MN, USA), and composed of Nextel® 610 pure alumina fiber combined with pure aluminum. We first place focus on the uniaxial tensile behavior of these composites. We then turn to the interaction of torsion with tensile deformation and fracture of the wires. This takes several forms, which we address in turn: (i) torsion of the wire causes a change in its length (this is called the Swift effect [9]), (ii) tensile deformation of a pre-twisted wire causes a certain degree of untwisting of the wire (this is called the Inverse Swift effect [10]), and (iii) twisting the wire alters its longitudinal tensile strength.

EXPERIMENTAL PROCEDURE

A - Materials

The material investigated is a continuous metal matrix composite wire containing 45 vol. % Nextel® 610 α-alumina fiber in a pure aluminum matrix. A cross-sectional view of the wire is given in Fig. 1, showing that the fibers are relatively well distributed in the wire, and that its cross-section is approximately circular. The average diameter of the wire was measured by image analysis to be 2.05 mm with a variation of 0.032 mm.

B - Tensile testing

Tensile testing was conducted following the procedure developed at 3M [11]. This procedure consists in gripping the wire at both ends using steel tubes 150 mm long, having inner and outer diameters of 3 and 6 mm, respectively, and within which the wire ends were held over a length of 100 mm using a high-strength epoxy glue, Fig. 2. In order to assure that the wire was placed in the center of the tube, wire and tube were fixed into a specially designed mold while curing the epoxy glue. Curing consisted in a 1 hour bake at 125°C.
Specimen with 50 and 250 mm gage length were thus produced, and tested in a Zwick 010 (Ulm, Germany) table-top tensile testing machine. Deformation of the wire was measured using a clip-on extensometer having a gage length of 10 mm and a resolution < 0.1 µm. Deviation from linearity was smaller than 1µm over the whole range of travel of the extensometer, in the vicinity of ±1.25 mm.
Matrix plastic flow and average internal stresses in the matrix were characterized using tension-tension cycles with a lower to upper stress ration R of 0.3.

C - Torsion of the wires

The glued tensile specimens were twisted to various controlled angles in a lathe. The specimens were gripped along the steel tubes; since the wire was centered in the tube, bending of the wire was kept at a minimum with this procedure. During torsion of the wire, one end was let free to move in the axial direction so as not to apply tensile stress on the wire. Surface

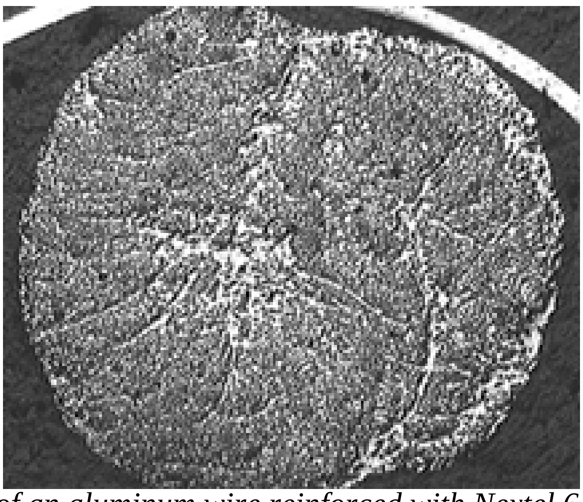

Fig. 1: Cross-section of an aluminum wire reinforced with Nextel 610 a-alumina fibers as used in this study. The fibers are evenly distributed within the approximately circular cross-section.

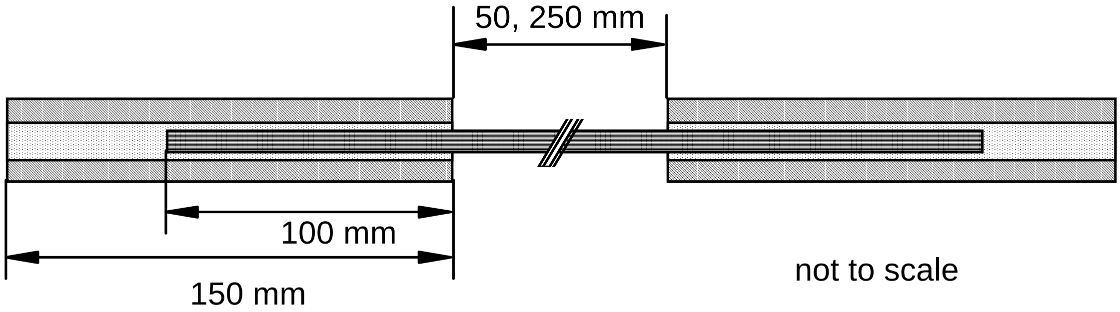

Fig. 2: Design of the tensile specimen as used in this study. Both ends are glued into steel tubes over a length of 100 mm to allow for transmission of the force by shear and gripped only at the ends where the tube is hollow to avoid stress concentrations.

shear deformations between 0 and 15% were introduced by this procedure.
The influence of pre-torsion of the wire on its tensile strength was investigated by testing the wires as described in Section B. In order to separate the intrinsic influence on strength of torsional deformation from that of damage introduced during torsion, a batch of samples was twisted and untwisted to their initial configuration before tensile testing.

D - Measurement of the Swift and Inverse Swift effects

The change in length of a wire during twisting, i.e. the Swift effect, was measured using a specimen prepared as described in section B, but having a gage length of 515 mm. At the center of the gage length another short piece of steel tube (15 mm) was centered and glued onto the wire in order to separate the gage length into two similar halves, 250 mm in length each.
Both tubes at the ends of the wire were fixed into the tensile test machine and a preload of 100 N (small compared to the fracture load of about 4 kN) was applied. The machine was then run in load control to hold the applied load constant. The preload ensured that the tubes did not slide in the grips. Then the centerpiece was twisted giving rise to equal and opposite twisting of both halves of the gage length (barring any rotational asymmetry). As the applied load on the wire was held constant, the elastic deformation of the wire as well as that of the load frame were constant, at least in a first order approximation. The axial strain in the wire could thus simply be measured by dividing the movement of the crosshead by the gage length of the wire as a function of the twisting angle.
The amount of untwisting of a twisted wire under external load, i.e. the inverse Swift effect, was measured using the same type of specimen. A plate resembling an optical encoder was fixed at the centerpiece. This device had an angular resolution better than 2°, corresponding for this sample geometry to a resolution in surface shear strain of 10^{-4}. Specimens were first twisted to various controlled angles of pre-torsion, corresponding to surface shear strains between 2.5 and 15%. The samples were then loaded in tension in increments of 100 N, after each of which the untwisting angle was measured. Some dependence on time of the untwisting angle measured after increment was noted. For this reason, reported untwist angles were measured after a fixed time increment of 50 s after the load increment. Since untwisting rates at this time were negligible, measured angles are close to the equilibrium angle expected for long waiting times.

RESULTS

A - Untwisted wire

The untwisted wire features an average fracture strength of 1.32 GPa. Most of the low-strength specimens broke at the very end of the glued section, indicating that stress consentration at these points probably caused premature failure. No significant difference was observed between specimens having a gage length of 50 mm and those with a gage length of 250 mm.

The stress-strain curve of the composite showed the classical bilinear behavior expected of a metal matrix composite. The initial slope in tension was about 210 GPa, after which the slope decreased to about 180 GPa.
Cyclic tension-tension curves with R=0.3 also showed such bilinear behavior, caused by reversed yielding in the matrix during tensile unloading (i.e., a strong Bauschinger effect was found), as expected for this kind of composite. The matrix average plastic flow and residual stresses were determined from these curves following the procedures described in Ref. [13]. By this method the yield stress of the matrix was determined to be 25±5 MPa. The average residual stresses in the matrix was found to vary significantly from sample to sample, within the range of 0 to 10 MPa in tension and with an average near 5 MPa.

B - Swift and Inverse Swift effects

Significant length changes of the wire were observed during twisting, and the various tests yielded reproducible results. An increasing shortening of the wire was measured as the twist angle–and thus the surface shear strain–increased, Fig. 3. This length change was found to be reversible, i.e. on untwisting the wire would return to its initial length. The shortening due to twisting was also symmetric with regard to the direction of twisting.
Plots of reverse surface shear strain γ_O measured on pre-twisted wire under external load are given in Fig. 4. In general, the wire kept its angle of pre-twist to a certain load and then started to untwist gradually as the load increased past this value. The higher the initial surface shear strain applied by twisting of the wire, the lower the load at which gradual untwisting began, and the larger the reverse surface shear strain reached at a given load. The amount of untwisting per increase of external force increased at the beginning, and then decreased gradually as untwisting proceeded.

C - Tensile strength of pre-twisted wire

Some of the pre-twisted specimen deformed to small surface shear strains failed at the very end of the gage length, as did some of the specimen from the reference batch of twisted and untwisted wires; however, no correlation was found between such failure and the amount of twist/untwist deformation. For surface shear strains above 0.07 all specimens failed at an random point along the gage length.

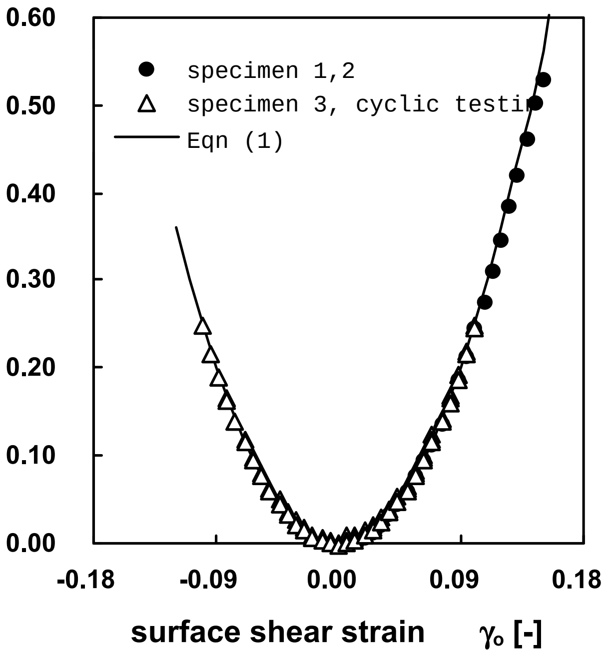

Fig. 3: Measurement of the length change due to twisting as a function of the applied surface shear strain. The wire generally shortens while twisted. On untwisting, the shortening was removed and the initial length was regained; thus, the shortening is a reversible process. Direction of twist had no influence on the results.

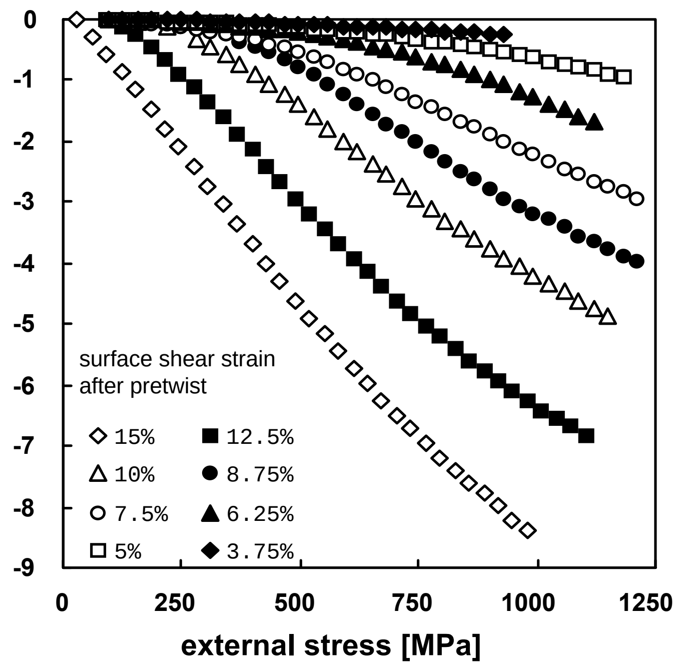

Fig. 4: Reversed surface shear strain as a function of externally applied stress for various initial surface shear strains. The amount of untwisting per increase in external force is the higher the larger the initial surface strain.

The fracture strength of pre-twisted wires is given as a function of the surface shear strain in Fig. 5. It is found that the tensile strength of the wires decreases steadily as the pretwist strain increases, with no influence of the gage length of the sample. This is in contrast to wires that are twisted and untwisted back to their original shape, which show no evidence of a decrease in tensile strength.

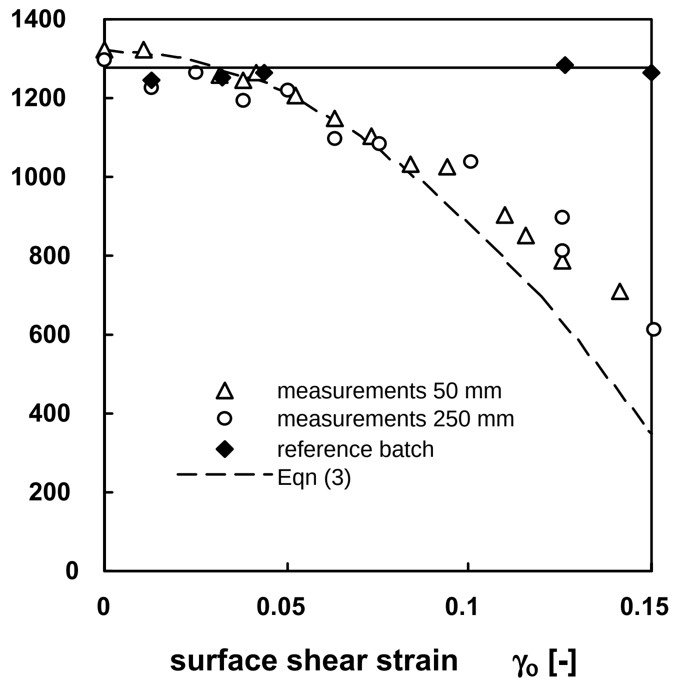

Fig. 5: Dependence of fracture strength on surface shear strain γ_o for both samples with 50 and 250 mm gage length, showing no significant difference. Compared to a reference batch that was twisted and untwisted and then tested to fracture, the twisted samples show significant decrease of fracture strength as γ_o increases.

DISCUSSION

A - Untwisted wire

The tensile properties of the wire material without any torsional pre-treatment are comparable to those given in the manufacturer's data sheet. Hence, the tensile testing procedure developed at 3M and used in this study can be deemed reliable.

Measured matrix average flow and residual stresses, as well as the matrix *in-situ* plastic flow behavior in the composite, are in good overall agreement with data for similar composites reported in [13]. This shows the strong influence exerted by differential contraction between matrix and fiber during cooling from composite processing temperatures, and also provides an indication that there has been some degree of relaxation of internal stresses in the composite, in agreement with the observation of a time-dependent untwist angle in inverse Swift tests.

B - Swift and Inverse Swift effect: analysis and comparison with experiment

The shortening of the wire can be explained as follows. Consider a bundle of long parallel fibers; when twisted, the fibers at the surface adopt a helical form. For a given fiber length, the length spanned by the helix is shorter than that spanned by a central, straight fiber. For long wires of aluminum/alumina composite, for which the interface is strong, such relative sliding of outer fibers with respect to inner ones is inhibited by the matrix; hence it is reasonable to assume that cross-sectional surfaces of the wire remain plane after twisting. As a consequence of twisting, the outer fibers are therefore elongated elastically in order to keep the same length as the inner fibers. Since for a body free from external forces the average stress σ_{av} is nil, the central (straight) fibers are loaded in compression. This leads to an overall shortening of the wire.

Neglecting second order effects such as the influence of variations in the composite Young modulus as the fiber is inclined with respect to the loading direction, it can be shown [12] that the macroscopic wire shortening strain ε_{av} is related to the surface shear strain γ_o that is applied by twisting by:

$$\varepsilon_{av} = \frac{1}{4}\gamma_o^2 \quad . \qquad (1)$$

A comparison of predicted and measured values for shortening are given in Fig. 3: the data are well described by the analysis. Furthermore, since the shortening is caused by elastic deformation of the fibers, the reversibility of the shortening and the symmetric behavior with respect to the direction of torsional deformation are both explained by the theory as well.

The untwisting of a pre-twisted wire under external load, shown in Fig. 4, is basically a process whereby equilibrium is attained between retaining forces in form of shear forces in the matrix and untwisting forces due to (i) work done by the applied force as the wire elongates during untwisting, as shown in the previous section, and (ii) a reduction of the elastically stored energy as internal stress levels—compressive in the center, tensile at the surface—decrease with untwisting.

In a first order approximation [12], we assume an ideal plastic material with shear yield stress τ_o. The surface shear strain γ_o at which retaining and untwisting forces are in equilibrium is related to the external stress σ_{ext} and Young's modulus of the wire E by:

$$\sigma_{ext} = \frac{\frac{4}{3}\tau_o - \frac{1}{12}E\ \gamma_o^3}{\gamma_o} \quad . \qquad (2)$$

It follows directly from Eqn (2) that as surface shear strains get large, the external stress at equilibrium gets small. This explains why the external stress to start untwisting the wire decreases with increasing pre-twist, as shown in Fig. 4. The values of γ_o for which σ_{ext} becomes negative reflect the situation where backtwisting forces due to internally stored elastic energy become large enough to unwind the wire spontaneously. The surface shear strain corresponding to $\sigma_{ext} = 0$ is that at which the maximum surface shear strain that can be stabilized by the matrix is attained.

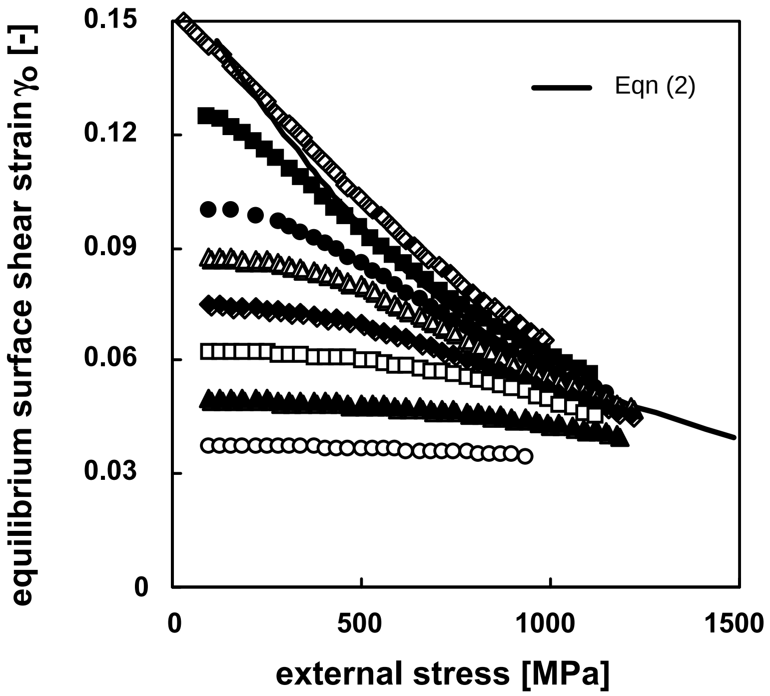

Fig. 6: Comparison of the measured equilibrium surface shear strain for various initial values as a function of the external stress.

As surface shear strains decrease due to untwisting, untwisting forces decrease and a higher increase of external stress is required to untwist by a given amount. This rationalizes the observation that the incremental amount of untwisting measured per increase of external stress decreases as untwisting proceeds.
The predictions of Eqn (2) are compared to measurements as given above in Fig. 6. For convenience the data from Fig. 4 are converted from surface shear values relative to the initial value after pre-twist, into values of absolute surface shear computed with reference to the undeformed wire. For the yield stress of the matrix in shear a value of 45 MPa was taken. Reasonably good agreement is found between Eqn (2) and the outer envelope of the experimental data.
Portions of the curve lying below this common envelope, for which the external stresses required to untwist the wire varies relatively little as untwisting proceeds, correspond to the situation where increasing parts of the matrix go from forward into reversed yielding as the applied load increases. Since in the simplified model that yielded Eqn (2) the matrix is assumed to be ideally plastic, an infinitesimal untwist would cause the whole matrix to go into reversed yielding. Thus, a description of transitory processes responsable for the parts of the measured curves that lie below the common envelope predicted by Eqn (2) would require a more elaborate model, which incorporates the influence of matrix gradual yielding and elastic deformation.

C - Strength of pre-twisted wire: analysis and comparison of theory with experiment

The results of the twisted wire testing are qualitatively in line with intuitive expectations, namely that the fracture strength would decrease as twist angle increases. Since the reference batch exhibits constantly high fracture strength, it is evident that the twisting procedure as such does not introduce any significant internal damage into the wire, Fig. 3.
Internal stresses, which cause the shortening of the wire as discussed in section B, can also be invoked to explain the evolution of wire fracture strength with initial pretwisting.
For simplicity, we treat the composite volume elements making the wire as elements which have a deterministic, fixed, fracture strength, instead of taking into account the statistical nature of composite fracture processes. Using a maximum stress criterion [14] and taking into account changes in Young's modulus due to misorientation of the fibers with respect to the loading direction at finite radii [8], the wire fracture strength as a function of the surface shear strain is predicted to be [14]

$$\sigma_{frac} = \sigma_o - \left(\frac{1}{4}\gamma_o^2 - \frac{5}{24}\gamma_o^4\right) \cdot E_o \qquad (3)$$

where σ_o is the discrete fracture strength of the composite volume element and E_o is the Young's modulus of the untwisted wire when the matrix is completely plastic. Values for these two parameters are taken from the tensile data, namely σ_o = 1320 MPa and E_o = 176 GPa. Good agreement is found between Eqn (3) and experimental data for surface shear strains up to 10%, as shown in Fig. 5. For higher surface shear strains, the analysis underestimates the fracture strength of the twisted composite. Two observations might explain this fact: (i) at surface strains higher than 10% fracture of individual fibers could be heard while the composite remained macroscopically intact. This indicates that at these high surface shear strains the simple maximum stress criterion used in the analysis leading to Eqn (3) no longer holds; (ii) measurement of the Young's modulus of the twisted wire indicate that the drop in Young's modulus due to misorientation of the fibers with respect to the loading direction is rather underestimated by the approximation given in [8]. This would then also lead to smaller internal stresses at the surface than estimated by the analysis, yielding in turn a higher fracture strength for the twisted wire.

CONCLUSIONS

The findings of this study can be outlined as follows:

1. Tensile tests conducted on Aluminum/ Nextel® 610 alumina fiber composites show good agreement with manufacturer's data. Load/unload cycles conducted during the test were used to measure the matrix plastic flow stress, as well as average matrix residual stress in the virgin composite.
2. Twisting of the composite wire results in a shortening of the wire that is proportional to the square of the applied surface shear strain.
3. Loading a twisted wire in axial tension results in untwisting.
4. Pre-torsion of the wire prior to tensile loading results in a gradual decrease of the fracture strength with increasing pre-torsion.
5. The amount of shortening of the wire, of untwisting under applied load, and the decrease in fracture strength as a function of pretwisting, can be explained based on an analysis of the internal axial stress distribution in the wire after twisting.

ACKNOWLEDGEMENTS

This work was supported by core funding of the Swiss Polytechnical Institute in Lausanne, and by a study grant from Erasmus student exchange program awarded to one of the authors (P. Canalis-Nieto). The authors also wish to thank Mr. Tracy Anderson and Dr. Colin McCullough of 3M, StPaul, MN, for provision of the composite wire material, for guidance in tensile testing of the wires, and for many stimulating discussions.

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