# REINFORCED TEFZEL WITH SHORT KEVLAR FIBERS

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## ABSTRACT

The Pulsed Plasma Thruster (PPT) uses solid Teflon propellant. The Teflon propellant is ignited with a small trigger discharge from the energy storage capacitor and electrodes. This energy will ablate the surface of the Teflon propellant and ionized plasma is created. The plasma is then accelerated by Lorenz force in the induced magnetic field to generate thrust. It has excellent propulsion characteristics (high specific impulse and small impulse bits) that become an excellent candidate for multiple satellite constellations. The weight of this small multiple satellite is very critical. If the solid fuel for station keeping and decommissioning can be used as load bearing material, the weight of the small satellite will be reduced. This reduction can increase the orbital lifetime or revenue-producing life of a communications satellite.

Teflon cannot be used alone as the load bearing material since the material is too soft. Reinforced the fuel with fibers is one of the options to enhance the structural performance of the fuel. A preliminary study using micromechanics theory showed that a significant improvement could be achieved with this reinforcement. Tefzel, a variant of Teflon, can also be used as fuel. It has better structural properties than Teflon and it is also lighter. A thrust testing of fiber-reinforced Tefzel has shown that Tefzel with 8 % fiber reinforcement only reduces the thrust by no more than 10%.

In this paper, we will present the experimental results of the reinforced Tefzel with short Kevlar fibers. Different fabrication techniques and fabric contents were used. Tensile tests were performed on these reinforced materials. The result showed an increase of more than 35% in elastic modulus for only 5 % fibers. The results were also compared with available analytical models. The analytical models over predicted the tensile modulus in general.

**KEYWORDS**: multifunctional structure, Tefzel, Kevlar, fabrication, tensile test

## INTRODUCTION

As modern spacecraft continue to become lighter and more compact, the spacecraft designer is called upon to integrate functional performance of several subsystems into fewer components. For example, Air Force Research Laboratory (AFRL) is developing the technology of multifunctional structures (Sercel et al, 1996; Guerrero, et al, 2000) to integrate the functions of load bearing, radiation and EMI shielding, and active thermal control as well as electronic components. As the developments in electronics miniaturization and microelectromechnical systems MEMS continue for longer-term spacecraft applications, further functional integration may be possible on the geometric scale of current or near-term spacecraft. Comparing with today's conventional satellites micro-satellites will bring new capabilities with cost reduction. Specifically, if the propellant for on-orbit propulsion could be obtained by consuming unneeded spacecraft structural members, substantial saving in spacecraft launch weight, volume, and/or increase in its orbital lifetime may be possible. These advantages are especially of interest to military and commercial communications satellites due to potentially reduced launch costs, greater payload, and increased revenues.

The present spacecraft design practice involves separate subsystems with dedicated functions, e.g., structural, thermal, power, etc. which are then integrated into a system called the spacecraft (Wertz and Larson, 1991). The primary function of the structural subsystem is to attach the spacecraft to the launch vehicle and to withstand and transfer (with amplification) the loads due to booster acceleration, random vibration, and transients resulting from booster and stage separations. A secondary structural subsystem function is to mechanically support other spacecraft systems and payload components, and store propellant and withstand its pressure on orbit. The structure is sized for the primary launch loads requirements with its stiffness such that its natural frequencies are decoupled from those of launch vehicle, propulsion system oscillations, and aerodynamic buffeting during ascent. Thus, structural mass is dictated essentially by the requirement to survive the launch environment within a factor of safety (typically 1.4). Once on orbit, the structural loads on the spacecraft are minimal, resulting from the deployment of solar arrays and booms, and attitude control thrusters and mechanisms. Most of the structure, except that required for radiation shielding of the payload, then becomes a parasitic mass.

The Pulsed Plasma Thruster (PPT) provides a propulsion system capable of ultra small impulse bit in a compact, low mass configuration. PPT uses a solid Teflon fuel bar. A spark igniter triggering an electrical discharge across the exposed surface of the Teflon produces a small amount of plasma. The plasma is accelerated by the electromagnetic force in the induced magnetic field to generate thrust. This solid fuel may be able to play multi-functional roles for both power and structural purposes. A trade study also showed that this multifunctional fuel is best suitable for a spacecraft that is on the order of 100 – 200 kg.

A preliminary study indicated the fuel (Teflon) itself is sub-par as a structural material (Ng and Buckman, 2002). Reinforcing the fuel material with fibers may increase the structural performance significantly to the point where the use of reinforced Teflon is quite attractive from a structural point of view. Tefzel, a variant of Teflon, can also be used as fuel in PPT. Tefzel has better structural properties. Thus, Tefzel is chosen to be the target in this present study. This paper will present the investigation of the structural material behavior of Tefzel reinforced with fibers.

## MATERIAL TESTED

The Kevlar was chosen to reinforcing the PPT fuel in the present study. Other fibers such as PBO may be considered in the future. Kevlar is described as para-aramid, belonging to a group of materials called liquid crystalline polymers that consist of parallel rigid, linear fibrils. The microstructure is anisotropic, with high tensile strength but low shear and compressive strength. The engineering properties are transversely isotropic. The properties of Kevlar are listed in Table 1. Kevlar fiber has shown a decrease on both tensile strength and modulus when aging at elevated temperatures as shown in Fig. 1. It is expected that the adverse effect on propulsion performance will be minimum with Kevlar. A thrust testing of reinforced Tefzel fuel has shown that Tefzel with 8 % fiber reinforcement only reduced the thrust by no more than 10% (Lengyel, 2002).

Tefzel, an organic compound, is an alternating copolymer of ethylene and tetrafluoroethylene. The comparison on mechanical and propulsion properties of these two fluoropolymers is listed in Table 2.

The propulsion characteristic of Tefzel is comparable to Teflon. The efficiency and specific impulse (measured thrust, propellant usage per discharge energy) are better for Tefzel. The only tradeoff is the low thrust/power ratio. Tefzel has lower viscosity, lower density, and higher strength than Teflon. In addition, the fabrication with Tefzel (lower melting point) means higher retention in Kevlar's strength than using Teflon.

**Table 1. Kevlar Properties**

| Property | Kevlar-49 |
|---|---|
| Density, $Mg/m^3$ | 1.44 |
| Fiber diameter, μm | 12 |
| Young's modulus, longitudinal, GPa | 112 |
| Young's modulus, transverse, GPa | 6.9 |
| Shear modulus, transverse-transverse, GPa | 2.6 |
| Poisson's ratio, longitudinal-transverse | 0.36 |
| Poisson's ratio, transverse-transverse | 0.36 |
| Tensile strength, GPa | 3.0 |
| Tensile elongation at break, % | 2.4 |

**Table 2. Properties of PPT fuels (Teflon and Tefzel)**

| Properties | Teflon | Tefzel |
|---|---|---|
| Density $Mg/m^3$ | 2.16 | 1.7 |
| Ultimate Tensile Strength (MPa) | 31 | 40 |
| Compressive Strength (MPa) | 15 | 17 |
| Melting Point (°C) | 327-342 | 230-270 |
| Thrust/Power (mlb/kw) | 4.74 | 3.61 |
| Specific Impulse (sec) | 5170 | 8410 |
| Efficiency (%) | 53.4 | 66.2 |

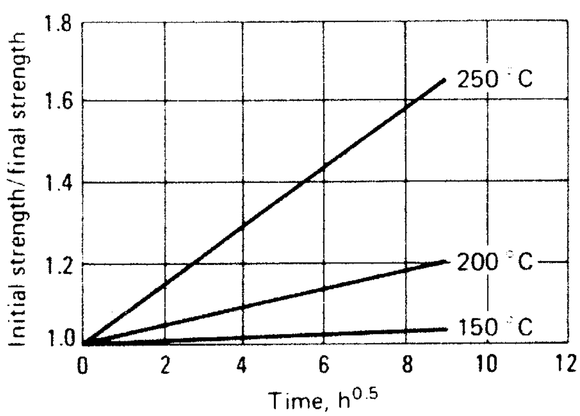


**Figure 1. Room temperature tensile strength retention after air aging of Kevlar aramid yarn at various temperatures (Pigliacampi, 1987).**

## FABRICATION OF TENSILE SPECIMENS

Compression molding at elevated temperature was used to coalesce the two materials. Three different molds have been tested and the steel mold as shown in Figure 2 was found to be the best. The specimen will have a shape of a dog-bone with dimensions as shown in Figure 3. The thickness of the specimen varies with the number of layers used in the construction. They were constructed by layers of Tefzel pellets with alternating layers of Kevlar short fibers (12.7 mm) reinforcement. The compression force was applied by two C-clamps. Then, the setup was put into an oven at 290 °C for one hour.

**Figure 2 Photograph of The Steel Mold**

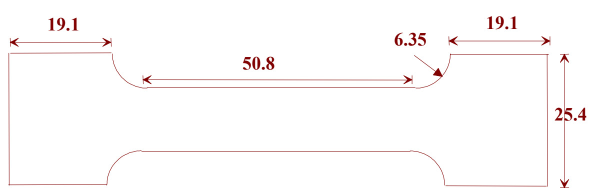


**Figure 3. Tensile Dog-bone Specimen Geometry Schematic. All dimensions in mm**

A total of 34 specimens were manufactured with three different fiber contents (2.5 %, 5 %, and 10 %). Figure 4 shows some typical specimens. The specimens were fabricated with different numbers of layers (3, 7, and 9 layers) to examine the fabrication process. Good consolidation was found in the current fabrication method; however, uniformity is still a concern. Dispersing the Kevlar fibers uniformly is still a challenge in the fabrication process especially with high fiber content. For specimens with 10% fiber, it was unsuccessful to produce good consolidated specimens with 3-layer and 7-layer construction methods. Only the 9-layer method yielded good specimens. There are still some dry fibers in these specimens.

## TEST RESULTS

The specimens (Tefzel-Kevlar composites) were tested with a MTS machine. The stress-strain curves for specimens with 5% fiber and different construction processes are shown in Figure 5. The elastic modulus is calculated by linear regression of the stress-strain data up to the axial strain of 0.005. Table 3 shows the ranges and the means of elastic modulus for the present study.

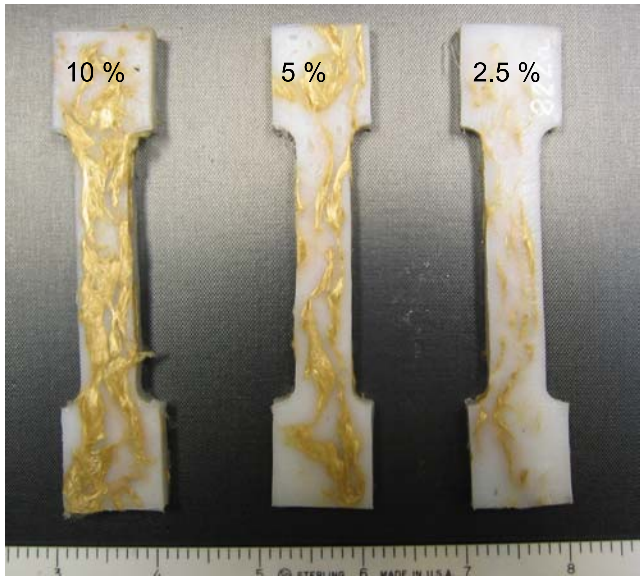


**Figure 4. Specimens with Various Fiber Contents**

**Table 3. Elastic Moduli of Specimens**

| Fiber Contents | Elastic Modulus (MPa) | | |
|---|---|---|---|
| | **3 layers** | **7 layers** | **9 layers** |
| 2.5 % | $1039^{+}$ (983-1133)* | | 1078 (930-1162) |
| 5 % | 1175 (915-1369) | 947 (866-988) | 1319 (1286-1342) |
| 10 % | | | 1109 (1055-1418) |

- **$^{+}$ The average value   *Range of the experimental result**

In general, an increase in modulus with found as the number of layers increases. Also, the scattering of the elastic modulus decreases with increasing numbers of construction layers. This is attributed to the degree of uniformity in the fiber distribution. The tensile modulus of specimens with 10% fibers is smaller than specimens with 5 % fiber contents. It is due to the poor wet-out of the fibers in the specimens. The highest stiffness and strength occurred for the 9-layer specimens with 5% fiber, which had an average elastic modulus of 1319 MPa (below 0.5% strain), and a strength of 16.8 MPa. There are 10% and 35% improvement in elastic modulus for specimens with 2.5 % and 5 % reinforcement fiber contents, respectively.

In any case, as the number of Kevlar layers increases, the composite properties should approach those of a homogeneous composite. For that reason, only the results for the 9-layer specimens with 5% fiber by weight were used for comparison with the model results.

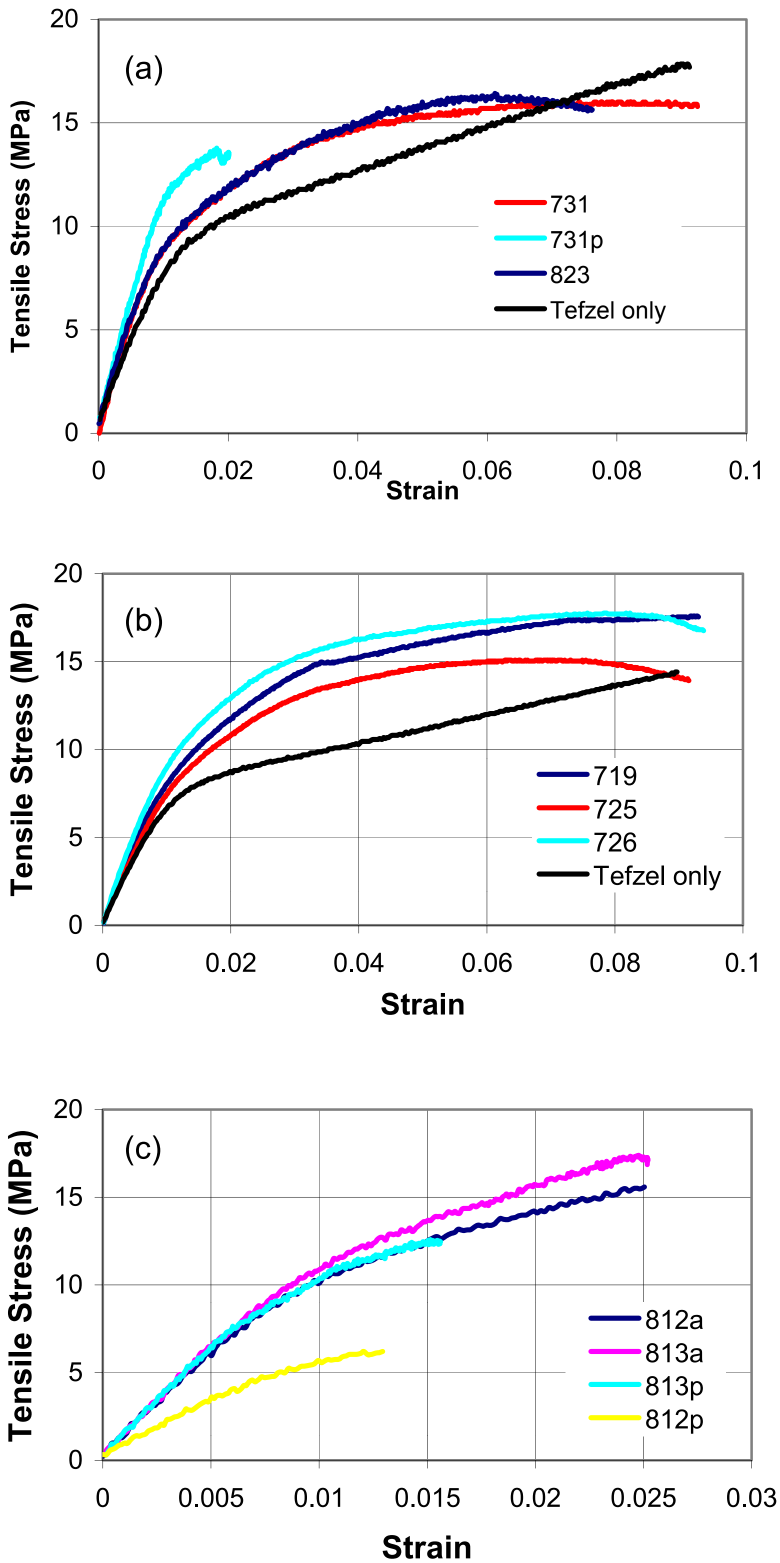


**Figure 5. Tensile Test Results of Specimens with 5% Fiber (a) 3-layer, (b) 7-layer, and (c) 9-layer Specimens**

## COMPARIONS WITH MODELS

Three models were selected in the present study. They are the rule of mixtures (Cox 1952), the quasi-isotropic laminate model, and the variational model (Eduljee and McCullouh, 1993). The result is shown in Table 4.

The rule of mixture equation follows that given by Cox. (1952). He analyzed factors for length and orientation angle that can be applied to the rule of mixture for continuous fibers. While it should be possible to extend the Cox analysis to a range of fiber lengths, an average length is assumed for this study and the variation in lengths is negligible.

In the quasi-isotropic laminate model, the laminate is assumed to be symmetric about the mid plane with layers at 0º ± 45º, and 90º. The longitudinal and transverse moduli of a unidirectional composite lamina with aligned short fibers were estimated by Halpin-Tsai equation (Halpin, 1969). The overall properties of the composite materials were estimated from the force equilibrium and thin plate theory.

The variational approach estimates composite properties from assumed stress/strain fields and energy expressions, with the goal of finding the elastic constants. The equations given by Eduljee and McCullough (1993) were used to estimate the elastic modulus. The fiber distribution in the composite is assumed to be randomly distributed clumps of aligned fibers. These groups of fibers are termed grains, and a grain is assumed to have homogeneous properties. A grain is analogous to a unidirectional laminate on a microscopic scale. Eduljee and McCullough assumed that this particular structure would result in a uniform strain field within each grain; so elastic constants for the grain can be obtained by the variational approach. The properties of the grain are estimated, and then the grain properties are averaged for orientation to get the elastic constants for the composite.

From Table 4, the variational method most closely estimates the modulus. Several factors could cause the differences between the results and the experimental data, including stress concentrations, inaccurate material data, or a weak fiber to matrix bond. Friedrich (1985) observed poor fiber-matrix adhesion with a Teflon matrix, and perhaps the lack of adhesion is responsible for the over prediction here. More information about the materials, such as the actual fiber lengths and distributions and the fiber-matrix bond effectiveness, probably would improve the estimates.

A comparison of the model features with the actual composite behavior may lend some insight into the reasons for the accuracy of the predictions. The variational method is the only model considered that explicitly accounts for stress variation near the fibers, and it gives the most accurate estimate (-4%). That stress variation may be a key factor in the composite modulus under low strains.

**Table 4. Comparison of Models for Elastic Modulus**

| | Experiment | Rule of Mixtures Equation | Quasi-Isotropic Laminate Model | Variational Method |
|---|---|---|---|---|
| **Elastic Modulus** | 1320 MPa | 2235 MPa | 1890 MPa | 1270 MPa |
| **Difference** | 0 | 69 % | 43 % | -4 % |

## CONCLUSIONS

Tensile tests were performed on Tefzel with Kevlar reinforcement. The Tefzel reinforced with whiskers exhibits an increase in elastic modulus. A 35% increase in elastic modulus was found with only adding 5% whiskers. The experimental data were also compared to three existing models. The stiffness was modeled with the rule of mixtures equation, a quasi-isotropic laminate model, and a variational approach. The models provided a range of results for elastic modulus. In general, the models tended to overestimate the composite stiffness compared to limited experimental data. The presumed cause may be some physical features of the composites not included in the models.

Future research should focus on improving the fabrication process to provide more uniform specimens. Better predication is expected with better and more uniform samples. The effectiveness of the fiber-matrix bond could be the key to prediction of composite stiffness and strength. The possible loss of fiber-matrix interfacial shear strength could be evaluated through tensile tests on single fibers imbedded in matrix material. In addition, electron microscopy of damaged samples could lend insight into the physical processes at work.

## ACKNOWLEDGEMENT

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