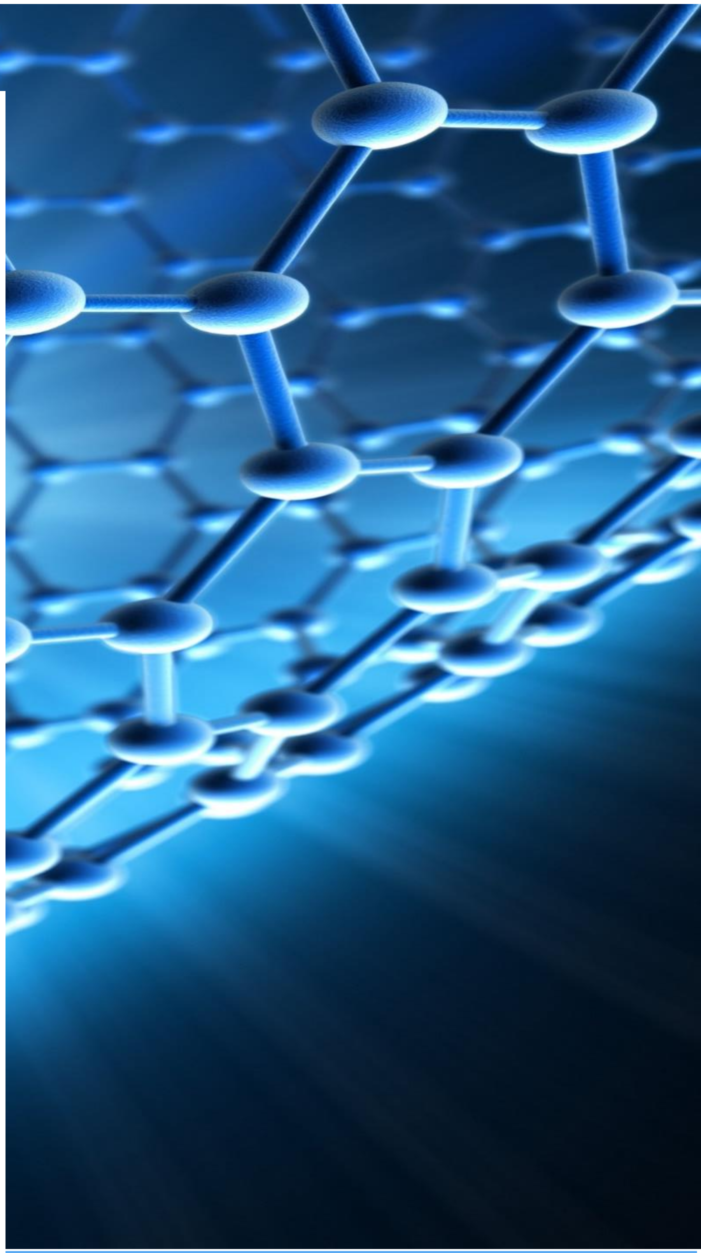

WHITE PAPER

GRAPHENE-ENHANCED TOUGHNED LAMINATING EPOXY KIT

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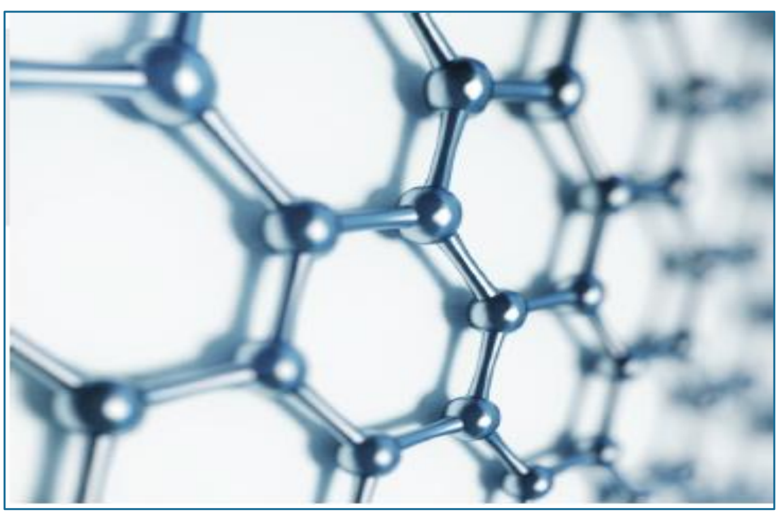
G6-EPOXY

The product series, G6-GTE55, are lightweight graphene-enhanced toughening epoxies, intended to be used as laminating resin for applications in aerospace, marine, automotive and defense. The addition of graphene, a nanoscopic reinforcing material (atomically thin carbon platelets), effectively improves performance of the laminating resin and the laminate composite as a whole. It was observed that graphene fillers significantly improve the mechanical properties of laminates. Graphene increases impact resistance and fracture toughness, as well as fatigue and corrosion resistance, thereby resulting in safer, lighter weight composite structures with a longer service life.

FAILURE IN FIBRE LAMINATES: IMPACT SUSCEPTIBILITY, FATIGUE AND ENVIRONMENTAL DEGRADATION.

There are many microscopic mechanisms of material deterioration that contribute to the damage and ultimate failure of laminate structures, e.g., fiber breaking, debonding of a fiber from the resin (interface failure), cracks or crazes in resins, and void growth (separation of layers forming the laminate, also known as delamination). For these reasons, to ensure the long service life of the composite, the selection of the materials used for making the composite is critical. The choice of reinforcement is important if stress corrosion is to be mitigated, while resin chemistry must be optimized to limit matrix damage. Fiber-matrix interface properties are also critical when composites are immersed for long periods. The failure mechanism in composite materials strongly depends upon the type of fibers used for reinforcement. Glass fibers tend to perform well under impact loads, while carbon fibers are relatively more brittle. An effective strategy for improvement of impact resistance is the use of additives that improve resin-fiber adhesion and ductility of the laminate. Glass fiber laminates tend to suffer from fatigue that can be strongly accelerated by environmental degradation. Therefore, the introduction of graphene additives into the resin to reduce brittleness, promote ductile non-destructive energy absorption and inhibit crack formation is highly desirable for longer service life and reduced repair costs.

GRAPHENE MATERIALS AS A REINFORCING AGENT FOR FIBRE LAMINATES



Graphene, the thinnest material in the universe, has transformative potential and application in multiple industries. The 2010 Nobel Prize in Physics was awarded to A. Geim and K. Novoselov for their discovery of the unique properties of graphene. Graphene is readily visualized as a hexagonal lattice of carbon atoms in a honeycomb-like structure. Layers of graphene are stacked to form graphite having an interplanar spacing of 3.35 Å. Graphene's crystalline structure affords its unique optical, thermal, mechanical and electrical properties. Graphene is the strongest material ever tested, having an intrinsic tensile strength of 130.5 GPa and a Young's modulus of 1 TPa. [1]

The graphene nanoplatelets are the small particles with lateral size of 0.2-25 µm and thickness varying from one to several dozen atomic graphene layers. Graphene nanoplateles are produced in the form of a low-density black powder that can be utilized as a reinforcement agent in various polymer composite materials including thermoplastic resins. With its high surface area, the addition of less than 1% graphene to a polymer is enough to significantly improve the properties of neat resin.

ROUTES FOR IMPROVEMENT OF FIBRE LAMINATES WITH GRAPHENE NANOPLATELETS

Despite glass and carbon fiber laminates being widely available and produced in a variety of formulations, there continues demand for improved performance of such laminate composites. In particular, fatigue and microcracking endurance are physical characteristics recognized as needing improvement. Fiber-based materials have incredible mechanical strength, but often lack stress and impact resistivity. The Company's toughened epoxy, G6-GRTE, formulated as a laminating resin for use in manufacturing of innovative light-weight graphene-enhanced materials and composites shows marked improvements compared to typical fiber laminates.

Impact Resistance: Graphene nanoplatelets substantially improve the impact resistance of the laminate carbon fiber epoxy composites by modifying the composites. There are several contributing factors: improved adhesion of the fiber to the matrix, inhibition of the crack propagation by nanoplatelets and improved interlayer adhesion strength.

Crack Resistance: Graphene materials have clearly demonstrated ability to mitigate crack formation in resins. Incorporation of graphene as a nanofiller in the Company's formulation considerably contributed to higher Mode II Fracture Toughness G_{IC} of G6-GTE55/carbon fiber laminate, which is improved by 47%. Mode II intralaminar fracture toughness in modified ASTM D5045 arrangement [2]. Moreover, the stress intensity factor K_{IC} of epoxy composite also exhibits a 4.4-fold improvement.

Improved Barrier Properties: Compared to metals, the composite materials are far more robust with respect to the damaging effect of the environment and moisture. Yet, the matrix of the composite is prone to deterioration by water damage. The most lucrative advantage of the graphene nanofiller is the impressive barrier resistance that it offers. Being impermeable to water molecules, the graphene nanoplatelets substantially slow down the water penetration inside the matrix, thereby protecting the matrix material against hydrolysis. The composite's capability to withstand corrosion is correlated with its water absorption rate. This parameter has improved by 20% for the enhanced epoxy resin.

Better Thermal Stability: Temperature significantly affects the behavior of polymers and laminates and, as such, must be carefully considered especially when designing vessel components because of direct surficial sunlight exposure. Polymers have an amorphous structure with a distinctive glass transition temperature (T_g) at which the material shifts from glassy (rigid) to rubbery behavior. Laminates lose effectiveness when they operate at temperatures above the transition temperature. The glass transition temperature is strongly dependent on the cure schedule. The matrix being cured at room temperature, without applying external heat, has the lowest possible glass transition temperature.

The Company's graphene-enhanced resin, G6-GTE55, optimizes the transition temperature by 15-20°C, significantly expanding the operation range of the laminates. Moisture absorption markedly reduces the glass transition temperature. Thus, the aforementioned improved water resistance is another factor to be considered when the composites are to be used in a humid environment. An example is the composite being used for making marine vessels. These composites are employed in a highly humid environment and potentially could be exposed to high temperatures during the operation of marine vessels.

Improved Interfacial Adhesion Strength: When the composite is under a load, most of its stress is carried by the fiber structure. But first, the stress must be transferred from the matrix to the fiber structure. Thus, the performance of the composite is strongly dependent on the strength of the bonding between the matrix resin and the fiber. The short beam strength test as discussed in ASTM D2344 [3] is an indicator of the adhesion of the fibers to the resin as determined by the Interlaminar Shear Strength (ILSS) parameter. The Company observed that the introduction of the graphene nanoplatelets to the resin lead to a 20% improvement of the ILSS as compared to a composite made with a regular, unmodified resin.

Increased Tensile Strength and Stiffness: The tensile and flexural moduli are indicators of the stiffness of a material. These properties of laminating composites are mostly determined by fiber reinforcement. However, the toughening of resin can improve the overall performance of the laminate. The Company observed that the flexural modulus improved by 20% and tensile modulus also showed some but lesser improvement. The Company attributed these improvements to better adhesion of the fibers to the matrix resin.

Better UV Stability: Infusion of the graphene nanoplatelets into the matrix resin greatly improves the UV resistance of the composite material. The penetration of UV light at a wavelength damaging to matrix resin will be prevented mostly by the optical density from the graphene nanoplatelets dispersed in the matrix. Graphene naturally has a very broad optical absorption spectrum. Each layer of graphene absorbs approximately 2.7% of the incident light [4] and the absorption grows accordingly with the number of layers and this phenomenon helps explain the deep, black color of graphene nanopowder. Also, graphene nanoplatelets offers an effective mechanism of quenching the electronic excitation being imposed by the absorbed UV photon, thereby preventing photo-damage of the composite [5].

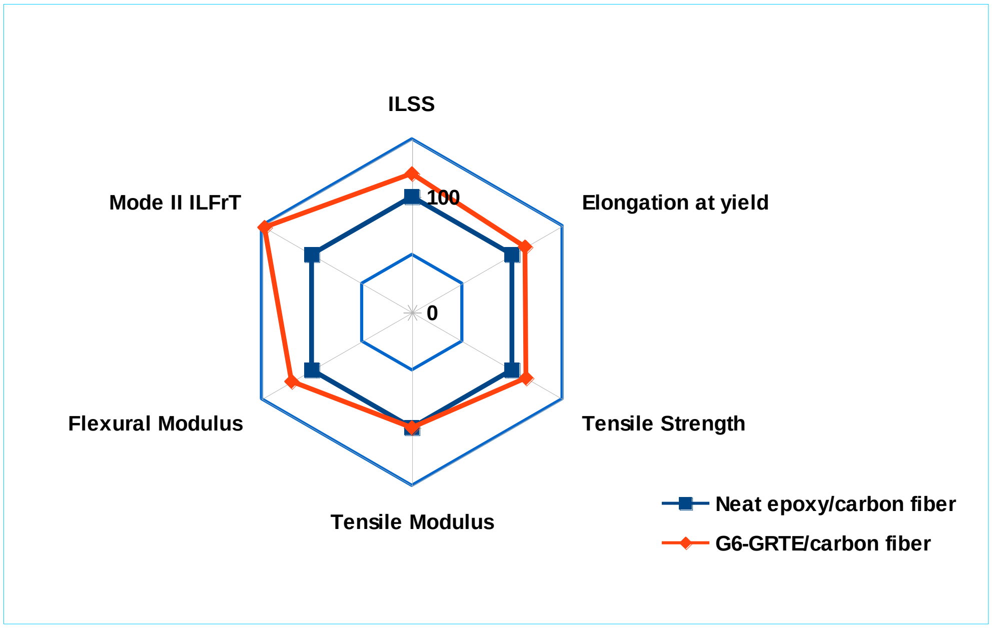
CASE STUDY

There are multiple types of laminating resin epoxies available on the market. Graphene additives described herein can be used for enhancement of any of the type. To illustrate the improvement of the performance of the material by graphene-based additive, the Company chose a generic laminating epoxy and analyzed performance of the resin and carbon fiber laminate with and without the graphene additive. The results of the analysis are presented below.

COMPARISON IN PERCENTAGE OF THE PERFORMANCE OF THE NEAT EPOXY RESIN via G6-GTE55

Test		Improvement, %
ASTM D5045	**Fracture toughness, Stress Intensity Factor K_{IC} (MPa·m$^{1/2}$)**	**×4**
ASTM D5045	**Fracture toughness, Strain energy release rate G_{IC} (kJ/m^2)**	**×14.2**
ASTM D570	**Water absorption, %**	**20%**
Solid Rheology	**Glass transition temperature, T_g, °C**	**+19 ^{0}C**
ASTM D638	**Tensile Modulus, E_{tens}, GPa**	**47%**
ASTM D638	**Tensile Strength, MPa**	**20%**

COMPARISON IN PERCENTAGE OF THE PERFORMANCE OF CARBON FIBER LAMINATE AT 80°C OF THE NEAT EPOXY RESIN via G6-GTE55



Test		Improvement, %
ASTM D2344	**Interlaminar shear strength, (ILSS) MPa**	**20%**
	Mode II Intralaminar fracture toughness G_{II}, MPa	**47%**
Solid Rheology	**Flexural Modulus, E_{flex}, GPa**	**20%**
ASTM D638	**Tensile Strength, MPa**	**14%**
ASTM D638	**Elongation at yield, %**	**13%**

Disclaimer: The information provided is based on data and tests believed to be accurate. Graphene Laboratories, Inc. makes no warrantees (expressed or implied) as to accuracy and assumes no liability in connection with any use of this product.

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FINAL THOUGHTS

The incorporation of nanomaterials in the fiber-polymer composite offers an exceptionally effective technique to improve the mechanical properties of composites. Fiber laminates that are currently being used in naval, automotive, military and aerospace applications can also greatly benefit from the incorporation of graphene. Graphene is a multifunctional filler that can simultaneously improve properties of fiber laminates while addressing critical performance drawbacks. The Company created a novel material, G6-GTE55, with improved resistance to stress, corrosion, cracking and fatigue. Additional benefits of the Company's graphene-enhanced resin include increased tensile strength and stiffness, reduced flammability, and improved thermal and UV stability. Therefore, the inclusion of graphene resins is expected to reduce the overall weight and cost of laminate structures and improve operational safety.