APPLIED GRAPHENE MATERIALS

Graphene Dispersions for Composites

Adrian Potts

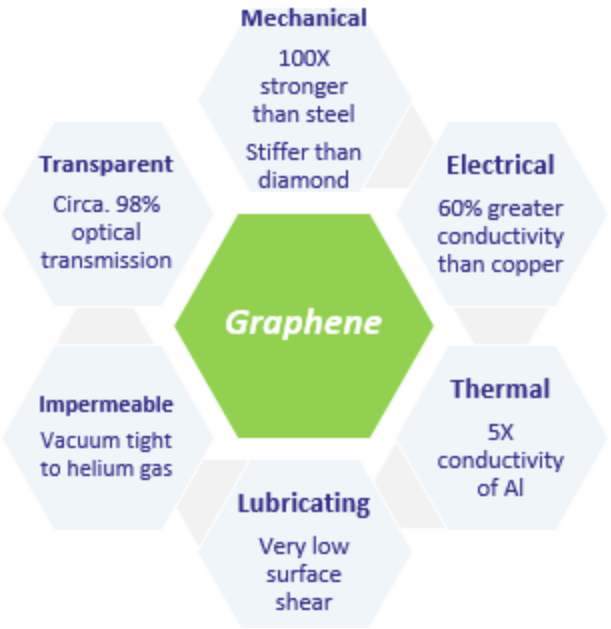
adrian.potts@appliedgraphenematerials.com

+1 (918) 344 8564

appliedgraphenematerials.com

Graphene – Fundamentals

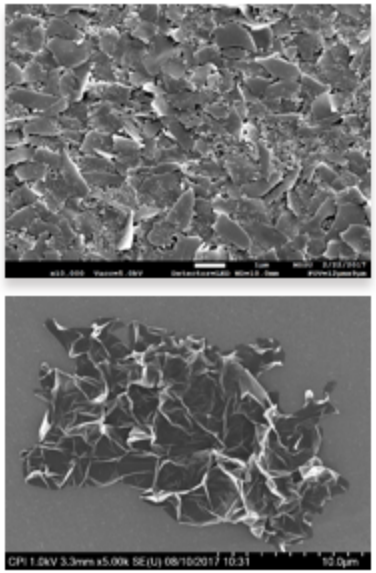
Single layer Graphene



It is a matter of matching the right material at a certain price point to specific application and performance objectives

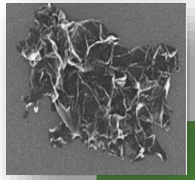
The Graphene Council Graphene Commercialization Report 2020

Graphene nanoplatelets



AGM – Enabling customers to succeed

Material Selection. Delivery mechanism. Ambition for performance.



Graphene Form

- CVD Film
- Single layer
- Few layer
- Graphene Nanoplatelets
- Reduced Graphene Oxide
- Graphene Oxide

Supply chain

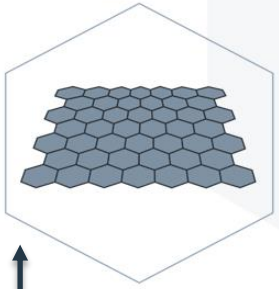
- Film
- Powder
- Dispersions

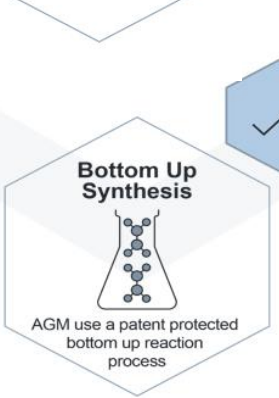
End Product

- Customer applications
- Performance ambitions realised

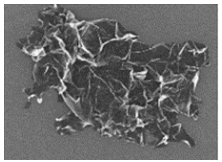
What we do - Synthetic Graphene Nanoplatelets

AGM - Differentiated synthetic GNP manufacturing.





- GNPs can be produced by molecular growth from small molecular carbon precursors
- Control - Number of layers
- Attributes - Surface area and high C content
- Process – Reliable, scalable method
- IP - Patented, know how, trade secrets and application experience
- Output - Useful powder additive to a range of applications



Standard Dispersions:

Genable®

- Distribution conduit with Standard products

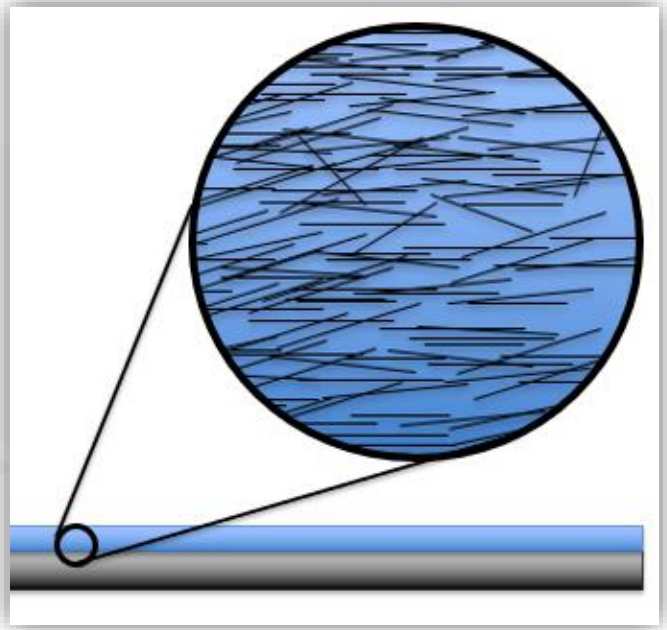
Customized Dispersions:

- Customer-specific dispersions to suit application
- Range of host materials which AGM has successfully dispersed GNP into
- Around 200 customized dispersions for customer development trials in the past 2 years.

What's Important?

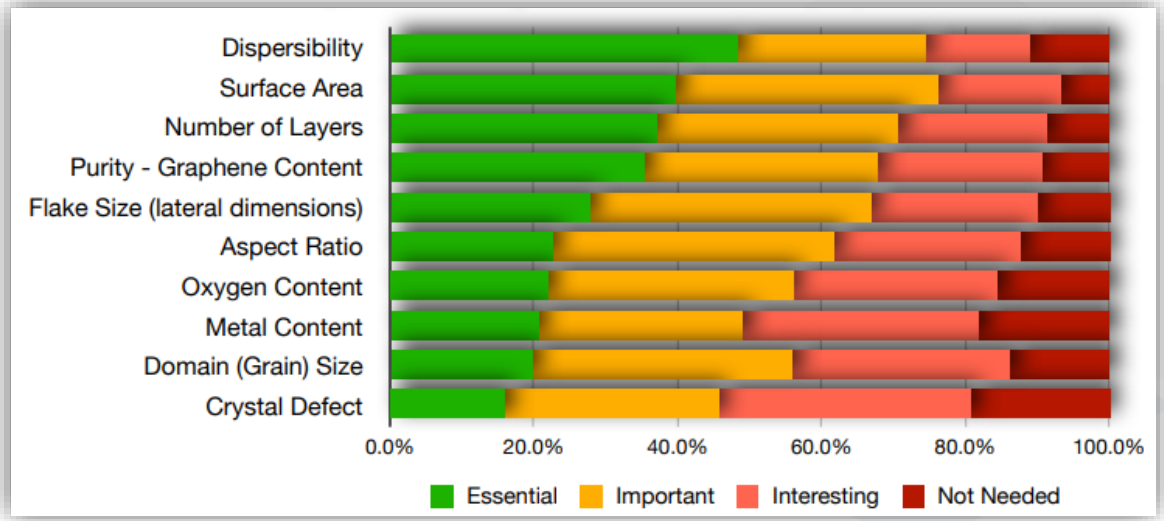
Principles to realise performance gains

- Why use high aspect ratio platy materials?
  - Use the aspect ratio to impart properties to:-
    - Matrix
      - Potential Mechanical uplift
    - Interfaces
      - Improve interface strength
    - Inter-plies
      - Improve interlaminar
    - Coatings
      - Barrier / Moisture pickup
      - Conductivity
        - Thermal
        - Electrical
  - High degree of platelet separation needed for success



What we do - Synthetic Graphene Nanoplatelets

Deploying Graphene Nanoplatelets



Courtesy The Graphene Council 4 Jan 2021 Survey on attribute importance

Industry need

- Dispersibility – key attribute
- Quality of platelets

AGM's focus

- Ability to realize the potential of GNPs in real applications
- Overcome the industry challenge of successful graphene dispersion

What's Important?

Principles

- How to get graphene into materials effectively?
- Particle size
  - Important for mechanicals through to other functionalities
- Aspect ratio
  - Is the process exfoliating further?
- Surface area
  - Adhesion to matrix through to absorption characteristics
- Loading level
  - GNP's very efficient when used in the correct way
- Compatibility
  - Chemistry of target product

Dispersion and process to arrive at "a fit for purpose solution" is critical

Composites / Graphene Background

Initial Technical Performance Approach

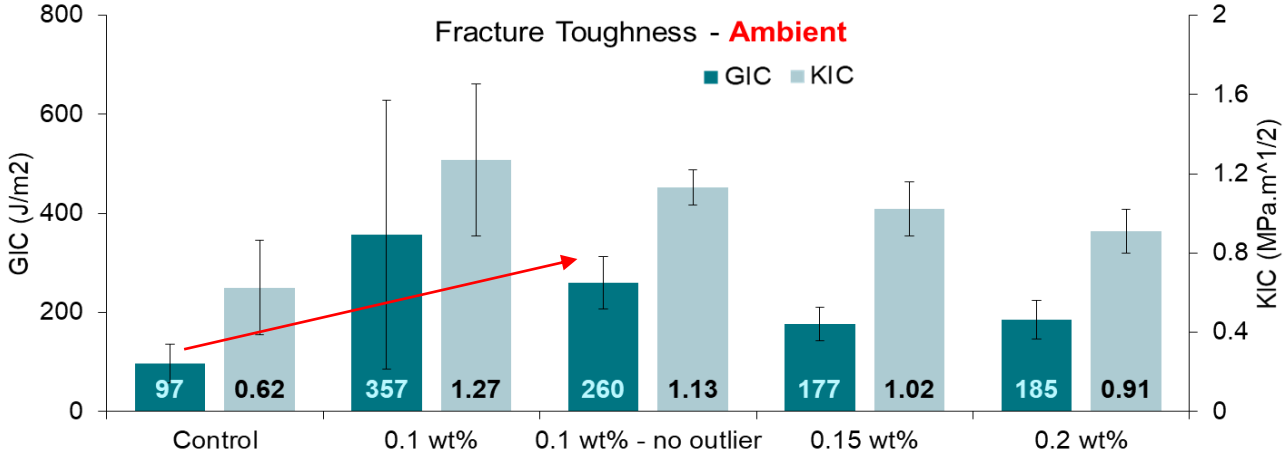
Add graphene platelets to matrix resin

- Basis – graphene has strength potential and low density. Also stiffness potential.
- Chemistry - If it can bond well to matrix, maybe greater load transfer possible
- Fracture Mechanics – Nano materials present to act as crack stopper/deflector to aid toughness and durability

Objective to enhance all round performance for matrix-dominated properties

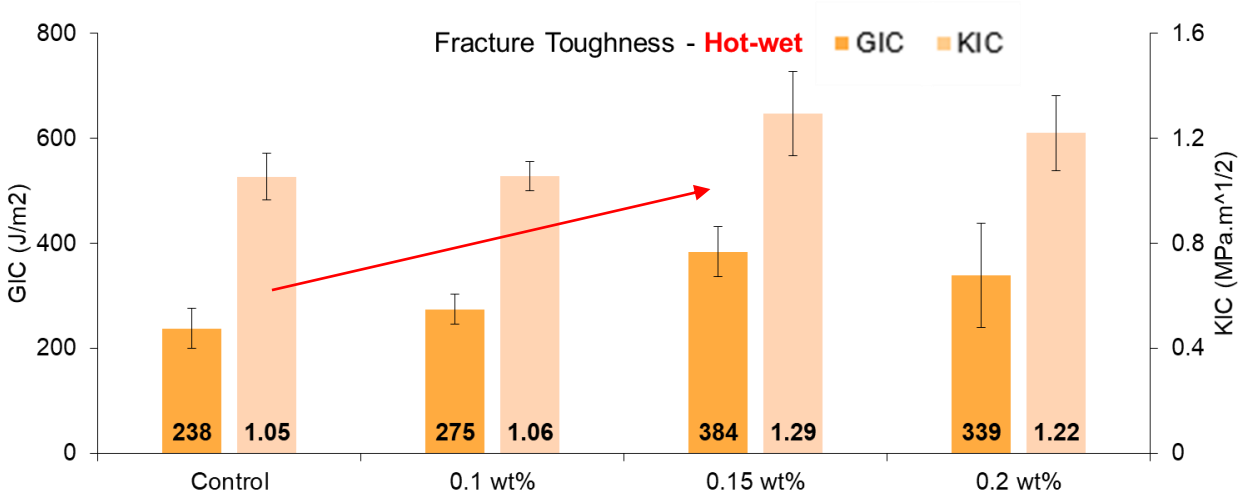
- Fracture Toughness
- ILSS
- Through-thickness performance
- Transverse tensile
- Shear performance
- Worry less about fiber-dominated properties – unlikely to influence

Fracture Toughness – Ambient



Ambient							
ID	Sample	G_{IC} (J/m²)	95C	% change	K_{IC} (MPa·m$^{1/2}$)	95C	% change
S1647	Control	96.75	38.61	n.a.	0.62	0.24	n.a
S1648	0.10 wt%	357.11	270.93	269.11	1.27	0.39	103.16
S1648	0.10 wt% **no outlier**	260.00	53.00	168.74	1.13	0.09	80.84
S1649	0.15 wt%	176.77	33.87	82.71	1.02	0.14	63.37
S1650	0.20 wt%	185.10	39.21	91.32	0.91	0.11	45.79

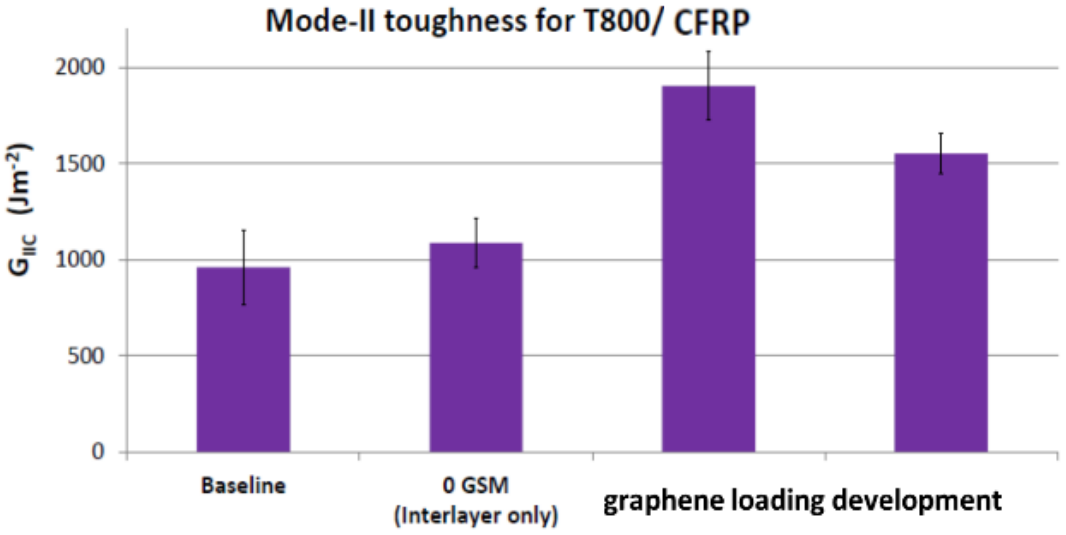
Fracture Toughness – Hot-Wet



Hot-wet							
ID	Sample	G_{IC} (J/m²)	95C	% change	K_{IC} (MPa·m$^{1/2}$)	95C	% change
S1651	Control	237.84	38.05	n.a.	1.05	0.09	n.a.
S1652	0.10 wt%	274.62	28.45	15.47	1.06	0.06	0.28
S1653	0.15 wt%	384.10	48.17	61.50	1.29	0.16	22.82
S1654	0.20 wt%	338.58	99.13	42.36	1.22	0.14	15.76

GIIC and LSS

Further toughening development with customers



Lap shear Properties

- Increase of **+25%** in lap shear strength and **+40%** in lap shear modulus with low loading levels of **G*enable*® Dispersion**

Composites Successes

Graphene nanoplatelets for lighter, stronger, cost effective composites for space

Customer Case Study

CHALLENGE

- Linerless composite tanks the holy grail of gas storage for space applications
  - Increase Performance
  - Reduce Weight
  - Reduce Cost
  - Reduce Lead time

- Potential - launch vehicles and satellite applications with ultra-lightweight storage tanks
- NASA programs such as Artemis and Lunar Gateway
- Next generation cryogenic pressure tanks a key technology to enable USA to maintain space superiority

Composites Successes

Customer Case Study – Tow winding

Graphene nanoplatelets for lighter, stronger, cost effective composites for space

SOLUTION THROUGH MATERIALS ENGINEERING

Liner removed through a combination of materials engineering with GNP's, manufacturing process and assembly design.

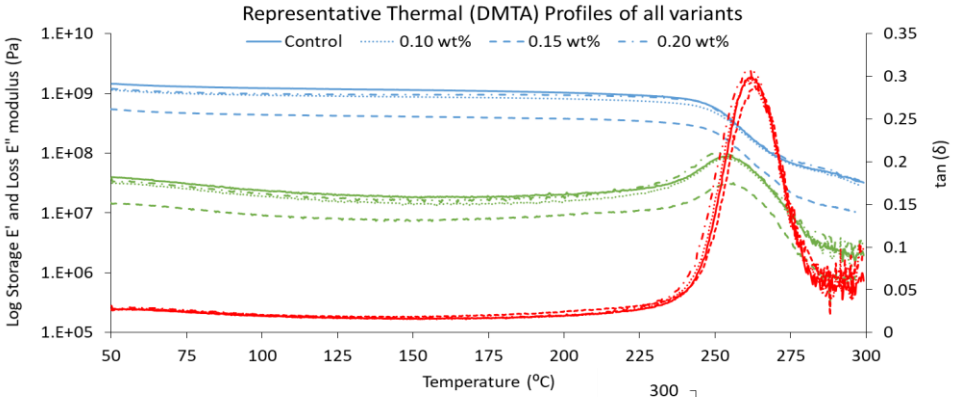
AGM GNP custom dispersions integrated into linerless composite matrix of pressurized tanks

- Enables tanks to be taken to higher pressures - **5000psi** gas storage capable
- Simulated **20 years life** – composite gets **stronger** over the pressure cycles with GNP addition

- Mass reduced **40%**
- Cost reduced **50%**
- Lead time reduced **80%**

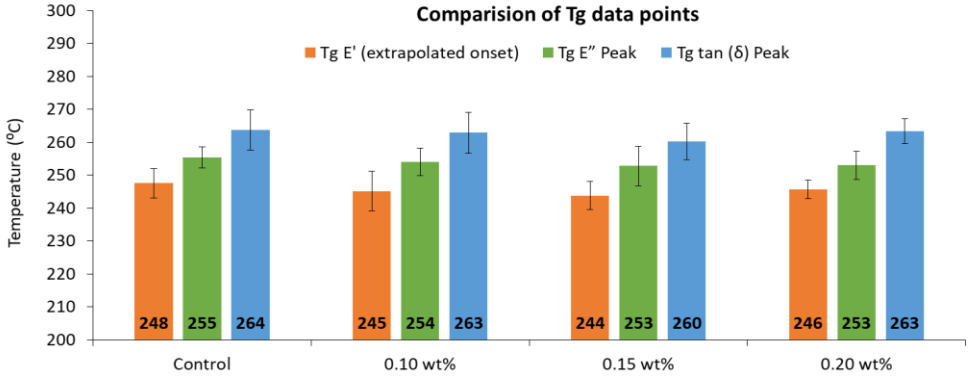
Potential for **Space**, **Aviation**, **Transportation** and **Industrial**

Tg effect

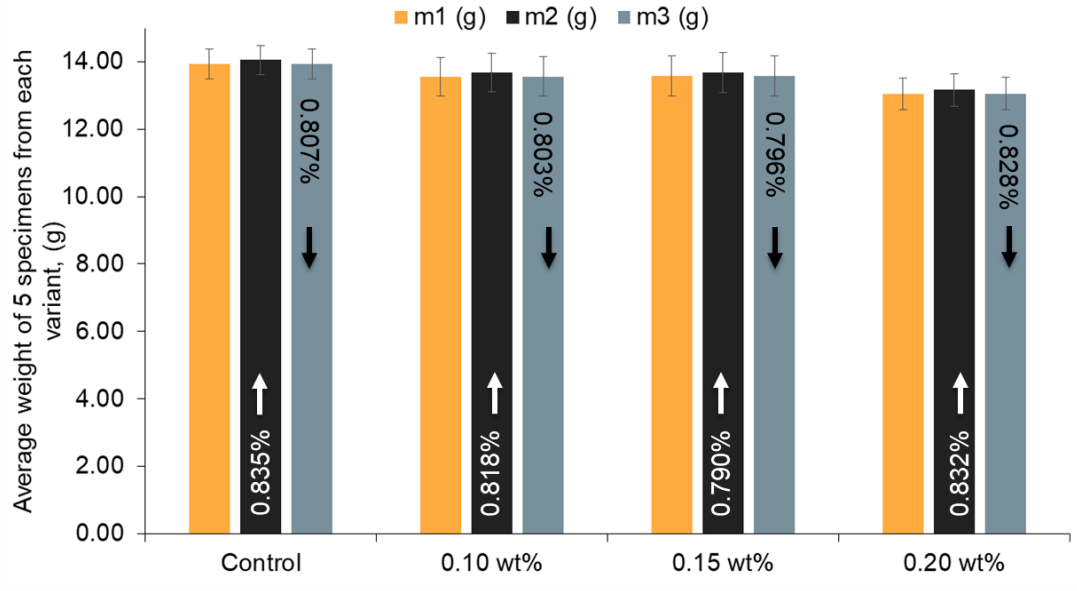


No significant change or shift observed in the thermal peaks and slops of all variants

The Tg of MY0510/LY976-1 remains unaffected due to the addition of AGNP35 in 0.1, 0.15 and 0.2 wt%



Moisture Uptake



m_1: weight after initial drying, m_2: weight after immersion (hot-wet), m_3: weight after final drying

- MY0510/LY976-1 or its AGNP35 modified variants do not absorb significant quantity of moisture during hot-wet conditioning (0.77% to 0.83%).
- The initial and final drying resulted in a similar transfer of moisture in-and-out of the system.

Composites Successes

Customer Case Study – MTC9810 Prepreg from SHD

G*enable*® 1000 resin dispersion with SHD Prepreg to achieve an enhanced fracture toughness prepreg system

Key Features & Benefits

- Excellent mechanical properties
- Very high fracture toughness
- Cure temperature from **90°C** to **120°C**
- Service temperature up to **110°C** after post cure
- Low CTE and shrinkage
- Work life at 20°C: **60 days**
- Storage life at -18°C: **12 months**
- Very low VOC content – no added solvents during manufacture
- Excellent surface finish
- **Honeycomb** bondable

Graphene enhanced prepreg used by W Motors

Good utility as enhanced performance prepreg material coatable on a wide range of fibers

Composites Successes

Successful Collaboration with Century Fishing Rods

SOLUTION THROUGH MATERIALS ENGINEERING

Century designed, tested and fully evaluated a range of next generation, graphene reinforced high performance fishing rods.

The **Century GT1000** rod was followed by extensive, and near destructive, field testing against large and powerful pelagic fish off the Ascension Islands.

Rods demonstrated clear performance benefits:

- Significantly reduced micro-crack development & propagation caused by the extended periods of laminate extension and compression
- Enhanced interlaminar strength performance
- Reduced surface degradation under harsh environmental conditioning, and
- Retention of all other laminate properties

Composites Successes

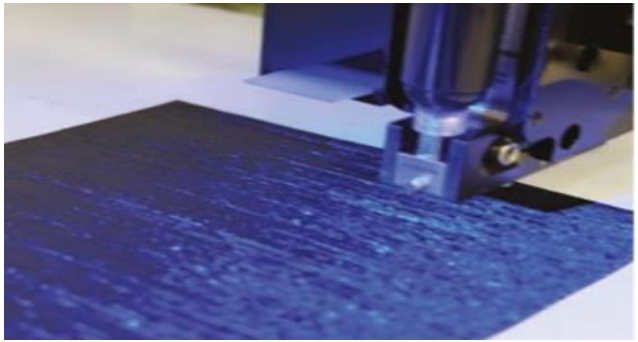
Customer Case Study – Automotive body panel systems

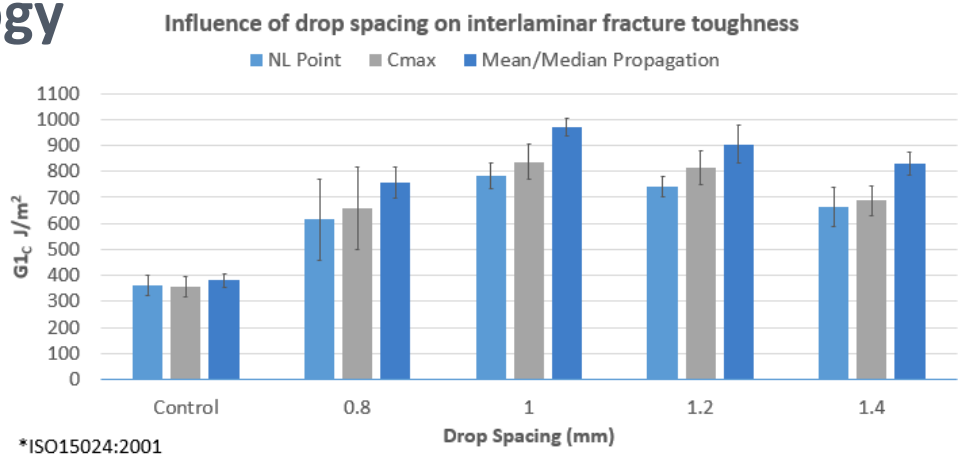
- **Scope:- Work with major automotive Tier 1**
- *"We can see positive directional improvements in key mechanical properties of composites systems. Encouragingly, other mechanicals investigated did not show significant change as compared to baseline numbers"*
- **Areas of substantial performance gain include:-**
  - Tensile Strength and Modulus improvements
  - Flexural Strength and Modulus improvements
  - Impact performance improvements
- **Alignment to trends in vehicle technology:-**

- **Potential to design out mass for light weighting through increased mechanical performance with graphene in a range of composites materials**
- **Chassis and body panels with range of composites process solutions**

Composites application technology

Printing graphene into composite layups





- Printed large platelet graphene for composites
- Formulated Structural Ink™ Graphene Ink printed onto composite materials
- Fracture toughness improvements in continuous fiber composites:-
- Matrix resin alone **+ 170%**
- Composite **+ 130%** and printing only where needed

- Other multifunctional possibilities with this technology

Possible options

Graphene Nanoplatelet Potential

- Objectives understanding
- Prepreg
- Resin for VRI or RTM
- Dispersions to suit application
- Printing
- Use of other graphenes or nano’s in our dispersions
- Sizing

Summary

Graphene Nanoplatelet Potential

- Mechanical performance gains achievable
- Matrix dominated properties – main area so far for improvement
- Possibilities for multi-functional benefits
  - Barrier / Moisture Uptake
  - Conductivity

- Selection of type of materials is important – just as you would with other elements of a composite
- Deployment method is key. Superior distribution of platelets to achieve performance ambitions