High Modulus Carbon Fibres in Super-Structural Compounds

INTRODUCTION

Carbon fibres are among the most popular reinforcement additives for polymer based composites, to be used in all those applications where very excellent mechanical performances are mandatory.

The technology of modern composite materials provides outstanding mechanical results to finished parts whose overall behavior can vastly exceed many metallic alloys, even the most sophisticated.

Despite of their exceptional characteristics, composites can not be easily handled and processed to obtain small complicated geometries featuring tiny details, elaborated contours, fillets and chamfers, peculiar curvatures and so on.

As a matter of fact, even if composite properties guarantee the best answer to the most severe project requirements, many industrial products can not exploit those advantages because of intrinsic limits of those materials e.g. concerning small scale shapes that can be manufactured.
Carbon fibres find successful application in thermoplastic compounds as well. Injection moldable reinforced grades are today available and can be obtained starting from almost any kind of polymer base, from polypropylene to PEEK.

Although fibre content in the compound can be raised up to **50%**, the technology of extrusion and injection molding induces a dramatic reduction of fibre length.
This phenomenon heavily influences mechanical properties that can be achieved by the compound in itself by the mean of stress transmission from the matrix to fibres.

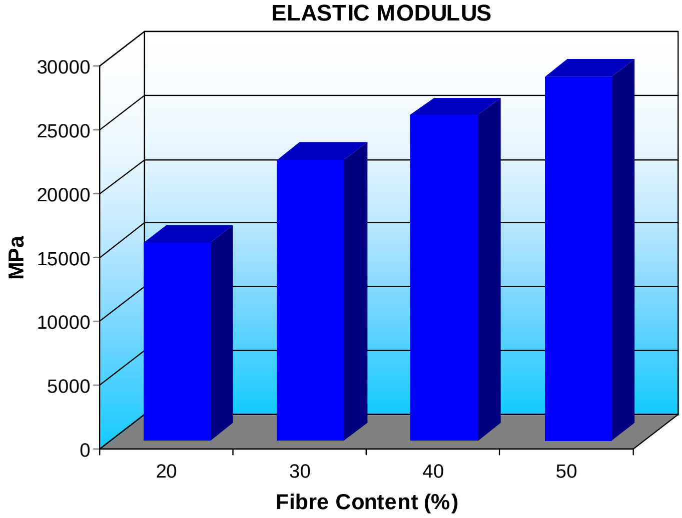

Fig. 1 Elastic modulus vs. carbon fibre content

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As evidenced in figures 1 and 2, elastic modulus and tensile stress at break of compounds can be efficiently enhanced by introducing a relevant content of high tenacity carbon fibres:

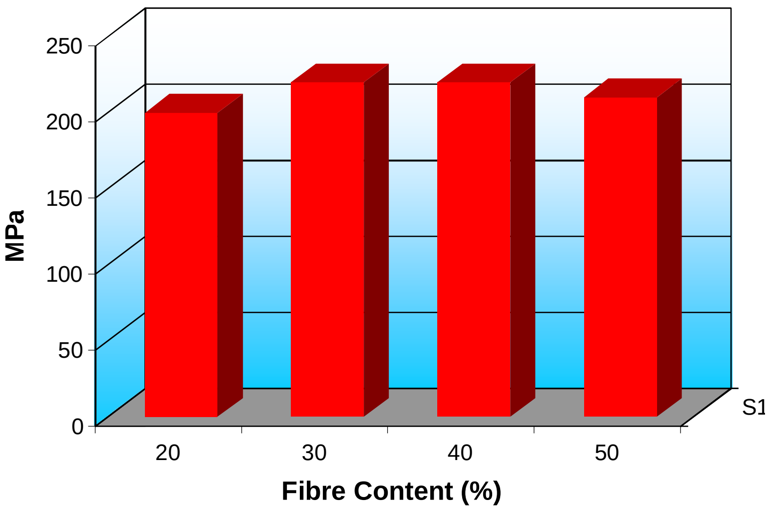


Fig. 2 Elastic modulus vs. carbon fibre content

Anyhow, experimental evidence indicates that it is not possible to further improve all mechanical properties, e.g. load at break, by incrementing the fibre content above a well defined threshold.

In any case, it is not possible to exceed a theoretical limit imposed by structure, dispersion and geometry of the reinforcement.

As a consequence, higher fibre contents generally offer a poor price vs. performance ratio.

METAL REPLACEMENT

Industrial development of new projects is anyhow more and more demanding.

The most frequently asked improvements concern:

- higher stiffness of injection molded parts, leading to extremely small deformations under load;
- increased compliance to design tolerances thanks to lower warpage and deflection of finished parts;
- enhanced capabilities in metal and thermoset composite substitution, introducing cost effective industrial manufacturing and environmentally friendly processes.

Those improvements are mainly imposed by the always growing precision required to parts and finished goods destined to the electric and electronic industry, fine mechanics, military field etc.

It is evident that new satisfactory solutions must be found by material specialists, even by overcoming difficulties related to intrinsic material and technology limits.

The target LATI decided to meet was to create a brand new range of injection moldable super structural compounds, successfully exploiting the dramatically higher elastic modulus of HM aeronautic purpose carbon fibers.

LATI HM – HIGH ELASTIC MODULUS COMPOUNDS

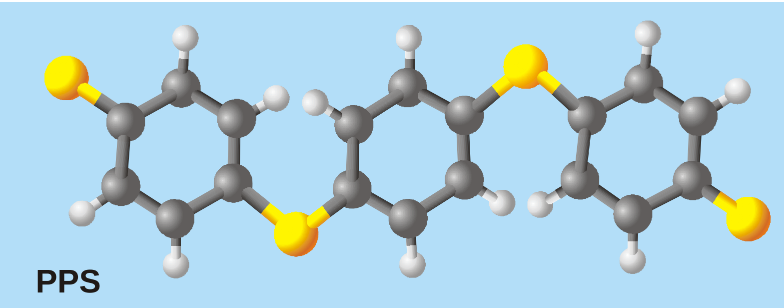
LATI faced the problem of creating this new breed of structural compounds by splitting research and development activities across three main branches.

A – identification of best candidate resins.

Being destined to top notch applications, only high end base resins have been adopted as matrix for the new-born compounds.
The polymers have been selected on the basis of mechanical, chemical and thermal performance.

PPS: polyphenilensulphide can be considered as the first step into the higher rank of thermoplastics thanks to its excellent chemical resistance and good mechanical performance even at temperatures above 200°C.

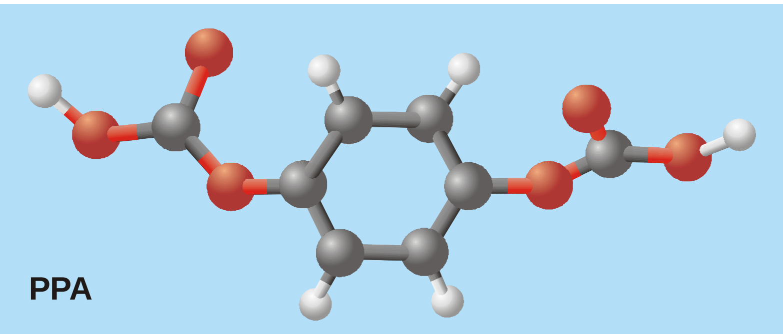
Its peculiar dimensional stability and stiffness make of PPS an excellent candidate for almost non-deformable compounds, as needed in many applications of precision mechanics.



PPS

PPA: polyphtalamide features excellent thermal and mechanical performance, specially considering tensile properties and resistance to creep and fatigue.
This resin can provide outstanding resistance to applied loads, both static and dynamic.

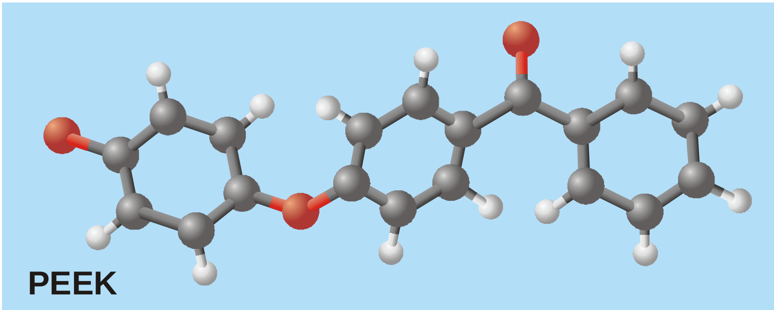
For this reason it turns out to be more suitable for impact resistant applications than PPA, and the best solution for vibration related issues.



PPA

PEEK: polyetheretherketone is well known as one of the best performing polymers thanks to its chemical, thermal and tribological characteristics which perfectly match the dramatic improvement of mechanical performance achieved by compounding with carbon fibres.

PEEK is strongly recommended for all no-compromise applications, as in the military, telecommunications and chemical industry.



PEEK

B – selecting special carbon fibres

Carbon fibres traditionally used in the thermoplastic compounding industry are chosen among high tenacity chopped strands, in order to increase elastic modulus and load at break without introducing excessive brittleness.

LATI wanted to test the properties of high modulus carbon fibre yarns and experimented compounding with these high-end reinforcement.

The difference between HM and HT fibres is evident: HM yarns show an elastic modulus that is almost twice the modulus of HT grades.

CHARACTERISTICS OF CARBON FIBERS				
Modulus	Low	Medium	High	Ultra-High
Name	HT (high tensile)	IM (interm. modulus)	HM (high modulus)	UHM (ultra high modulus)
Origin	Pitch	PAN	Pitch/PAN	Pitch/PAN
Density (g/cm^3)	1.78	1.76-1.80	1.79-1.80	1.90-2.00
Tensile modulus (MPa)	240.000	325.000	400.000	450.000
Tensile strength (MPa)	4.300	5.000	2.400	3.500
Thermal conductivity (W/mK)	17	17	17	-
Specific heat (J/KgK)	710	710	710	-
Volume resistivity (Ω/cm)	1.5 10^{-3}	1.5 10^{-3}	0.9 10^{-3}	-

Tab. 1 Analysis of the high modulus carbon fibre behaviour

C – tuning the compounding process.

Higher performance of HM fibers has to be transposed as much as possible to the thermoplastic compound.

This need does not cope with the typical conditions of the extrusion process, where very high shear stresses, relative speed and pressure normally lead to severe breakage of strands.

The resulting lack of integrity compromises the efficiency in the stress transmission mechanism occurring at the fibre-matrix interface.

As a general rule of extrusion and injection molding, length of reinforcing fibres must be kept as high as possible.

Several trials led by LATI technicians required fine adjustment of extrusion parameters and optimization of machine layout, specially concerning the carbon fibre feeding position along the extruder barrel.

Speed and profile of the plasticization screw have been optimized as well.

Collateral issues required adequate solution, as:

- fibre bundle built-up occurring during both the extrusion and molding process.
  Fibre bundles, favored by the length of the strands, would result in hindrance to the melt flow, carbonization of the polymer, machine jamming and defective parts;
- excessive viscosity of the melt compound. HM fibres were added up to 45% (weight) introducing a relevant volume fraction of non melting fillers. The viscosity of the melt had to be kept strictly under control to avoid poor molding and material degradation due to friction and shear;
- poor reinforcement dispersion. A uniform distribution of carbon fibres in the matrix had to be achieved to avoid a too wide scattering of mechanical properties between moulded parts.

The so created HM (High Modulus) family is today featuring three new and commercially available compounds, all reinforced by 40% HM carbon fibre:

- LARTON K/40 HM, PPS based;
- LARAMID D K/40 HM; PPA based;
- LARPEEK 10 K/40 HM; high fluidity PEEK based.

THE RESULTS

Benchmarks between LATI HM structural compounds and traditional grades show by far the superior performance of the HMs.

A – Elastic Modulus

Tensile tests, as per ISO-R-527, provide the first and most important answer about the real mechanical advantages of HM compounds.

This value has been boosted well above 40000 MPa, being 24000 a very good value for a general purpose 30% high tenacity carbon fiber reinforced thermoplastic.

Minor fluctuation of this value to be expected depending on the chosen matrix.

PPS in the HM version deserves a special mention thanks to its 49000 MPa bringing this grade in the field of proper metals.

Such a Young's modulus can evidently guarantee a much stiffer behavior of structural parts, allowing remarkably lower displacements of geometric features under load – as brackets, flanges, shafts, levers etc.

This pro may lead to plastic parts that – just like composites – can be considered as stiff as metal alloys for many engineering purposes, promoting both metal replacement and introduction of polymers in new demanding projects.

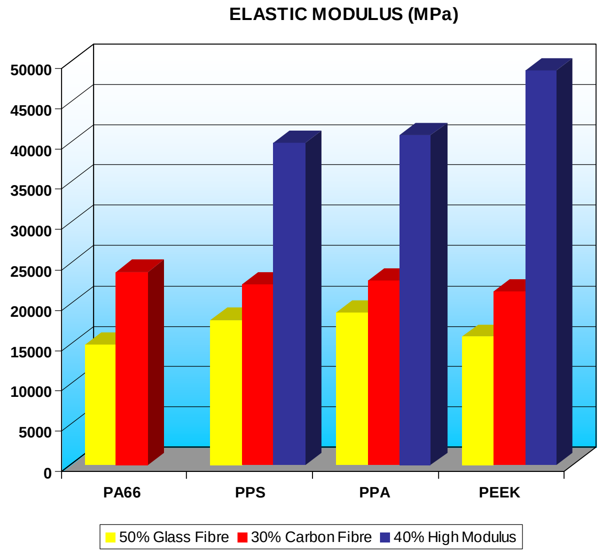


Fig. 3 Elastic modulus values MPa

COMPOUND		E (MPa)
PA66	50% Glass Fibre	15000
PPS	50% Glass Fibre	18000
PPA	50% Glass Fibre	19000
PEEK	50% Glass Fibre	16000
PA66	30% High Tenacity Carbon Fibre	23000
PPS	30% High Tenacity Carbon Fibre	22500
PPA	30% High Tenacity Carbon Fibre	23000
PEEK	30% High Tenacity Carbon Fibre	21500
PEEK	40% High Modulus Carbon Fibre	40000
PPA	40% High Modulus Carbon Fibre	41000
PPS	40% High Modulus Carbon Fibre	49000

As a term of comparison, it is possible to focus that the most popular structural compound available on the market, that is PA66 reinforced by 50% glass fibres, turns out to be three times "softer" than the best HM grade!

B – Fatigue resistance

Fatigue and creep performance can be influenced by amount and length of reinforcing fibres.
As a matter of fact, dispersed strands create a dense structure of entanglements into the polymeric matrix.

LATI HM products feature longer fibres than usual compounds using industrial grade chopped strand masterbatches.

For this reason a much better networking can thus be achieved and major improvements are allowed in:

- resistance to failure propagation through the matrix. The opening crack is hindered by the presence of longer fibres and for this reason an interesting improvement is noticed in both the number of cycles to failure and the stress at break occurring during fatigue phenomena;
- stress distribution during static and dinamic applications.

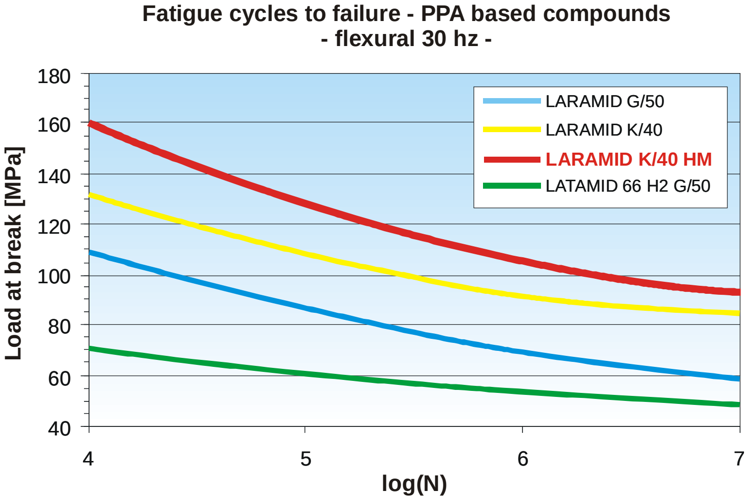


Fig. 4 Fatigue cycles to failure test

The difference in fatigue performance (load at break vs. cycles) is interesting when compared to other carbon fibre reinforced equivalents but results astounding versus PA66 reinforced with 50% glass fibres.

C – load at break

High carbon fibre content achieves not just enhancements in the tensile modulus but even in resistance of the compound.

An interesting step forward is measured in the load at break as well.

Of course, outstanding stress at break must be available if smooth metal replacement is the goal.

HM compounds can offer up to 280 MPa (tensile, as per ISO-R-527) on the PPA based grade – a value far beyond any optimistic expectation when talking about injection moldable thermoplastic compounds.

In fact, the best industrial structural compounds featuring 50 and 60% glass fibres can get only close to 220 MPa and with a much higher density.

COMPOUND	Elastic Modulus (MPa)	Load at Break (MPa)	Elongation at break (%)
PA66 G/50	15000	215	2,5
PA66 K/30	24000	240	1,5
PPS G/40	16000	160	1,2
PPS K/30	22500	185	1
PPS – HM *(ultra stiff)*	49000	200	0,6
PPA G/50	19000	265	2
PPA - HM *(ultra stiff)*	41000	280	1,5
PEEK G/40	14000	205	1,5
PEEK K/30	21500	225	1,5
PEEK - HM *(ultra stiff)*	40000	210	0,7

Tab. 2 Tensile test - as ASTM D256 norm

Many metal solutions, as die cast, pot metal or zamak, can not reach the **LATI HM** performance as well.

CONCLUSIONS

LATI HM compounds set a new reference point in structural thermoplastics, introducing on the market a new breed of injection moldable compounds that can be used in the most demanding projects where metal and composite can not be adopted or need to be replaced.

A great number of industrial sectors may benefit and get profit out of chances offered by HM compounds:

- aeronautic and military;
- precision mechanics;
- automation and robotics;
- textile industry;
- precision electric and electronics;
- renewable energies and green solution.

The properties of those grades match the well known advantages of injection molding technique, that is great flexibility, low equipment costs and fast industrial implementation of new projects.

Minor impact on environment and human health as well as easy disposal of scraps complete an already positive approach of this solution to new challenges of modern engineering.