

Family of High Modulus (HMG) Nylon Based Plastics Increases Mileage and Reduce Weight

ABSTRACT

Recent developments¹ were oriented on two high-flow, high-modulus grades fiber-glass reinforced nylon 6 (HMG series) grades for transportation, autos and other industrial applications requiring high stiffness, high strength and high fatigue resistance. These materials combined the following improved technological (injection molding, vibration and hot plate welding, etc.) and mechanical performance properties such as greater dimensional stability, higher short-term (strength and stiffness) and long-term (fatigue and creep with the influence of temperature effects).

Both HMG series grades Capron®² HMG10 and Capron® HMG13 – are for injection molded parts where stiffness, strength, impact resistance, and good surface and improved appearance are preferred. The current and possible applications of these plastics includes auto mirror housing brackets, clutch pedals, clutch master cylinders, ski bindings, steering wheels, levers, auto seat frames, door handles and door lock mechanisms.

INTRODUCTION

Surging transportation, automotive, appliances, electrical and electronics markets are given rise to a new high-performance nylon (polyamides - PA) that are challenging metals (steels and light alloys) and other engineering plastics on a cost and performance basis.

Thermoplastics offer the plastic parts designers and manufacturers the following key benefits – weight saving, improved performance and style [1]. Integration of function is a benefit in plastics injection molding, converting the assembly of multiple metal made from the past into today's. Different types of injection-molded nylon based plastics provide a wide range of end-use performance for various industrial applications. Nylons

(polyamides) are high performance semi-crystalline thermoplastics with a number of attractive physical and mechanical properties. There are more than a dozen classes of polyamide (PA)/nylon resins, including nylon 6, nylon 66, nylon 46, nylon 10, nylon 12, etc.

The analysis provided by APC (American Plastics Council) show, that the sale of the resin in 1999 reached the 45.5 million tons mark for the first time. Total sales of nylon were up 12.4% and production grew 5%. The thermoplastic growth continued in the global composites market in 1999 at a rate of about 4% in North America and 6% worldwide [2]. Some analysis³ predicts faster growth for thermoplastics – at 3.8% - to 65.4 million tons in 2001 [3]. At the same time, worldwide consumption of nylon (polyamides) is growing annually 8% to 9%. Much of the recent growth in nylon (polyamides) has centered on the automotive industry, where nylon/polyamide made parts are ending out various metals and in some cases costly plastics (including thermosets).

Short fiber-glass reinforced nylon (polyamides) offer thermoplastic part design an excellent combination of mechanical (short-term and long-term), physical and chemical properties. The current range of short fiber-glass reinforced nylon 6 based plastics are limited in their short fiber-glass content which is usually 30 ~ 33 wt.%, with a *maximum* of about 45 ~50 wt.%⁴. The following parameters of mechanical performance such as strength and stiffness may be low for some potential loads/stresses bearing applications.

Usually the higher properties were obtained by utilizing a concept of long fiber-glass reinforcement. Unfortunately, the mechanical performance level with long fiber-glass reinforcements is very sensitive to the part and molding tool design, compounding, and injection molding conditions. From this point of view, the short fiber-glass reinforcements are less sensitive to the above discussed key factors (part and mold design, compounding and injection molding conditions).

¹ Initially paper was presented to ATT 2001 (Automotive & Transportation Technology Congress & Exhibition). This paper received Best Paper Award for Materials Track.

² Capron® - is trade name of BASF Corporation nylon based plastic products.

³ Freedonia Group Inc. (Cleveland, Ohio)

⁴ wt.% - level of reinforcement or filled by weight.

High modulus and high strength (HMG series) materials are very important in the design of plastic parts, when structural requirements to NVH (noise, vibrations, and harshness) are a critical factor. Parameters of high stiffness of these materials will help to maintain rigidity of a structure itself, reduce vibrations and noise, and increase fatigue life (mileage). This market will have a big potential growth for HMG series plastics.

FIBER-GLASS REINFORCED NYLON (POLYAMIDE) IN AUTOMOTIVE AND TRANSPORTATION APPLICATIONS

The most discussed future direction for transportation and automotive material is that of the reducing weight [4-6]. While weight can potentially be reduced through design optimization of current materials, the large weight reduction needed in the future will lead to the consideration of low density materials for every part (where it is possible) of the vehicle.

Table 1. Weight Savings for Lightweight (LW) Materials and Thermoplastics [3]

LW Material	Material Replaced	Mass Reduction (in %)	Relative Cost ⁵
High Strength Steel	Mild steel	10	1
Aluminum Alloys	Steel, cast iron	40-60	1.3-2
Magnesium Alloys	Steel, cast iron	60-75	1.5-2.5
Magnesium Alloys	Aluminum Alloys	25-35	1-1.5
Fiber –Glass Reinforced Polyamide	Steel	25-35	1-1.5

Several of the low-density materials are currently being used in transportation and vehicle design, and they are increasing. Key advantages of thermoplastics such as nylon (polyamide), over steels and lightweight alloys include weight and cost savings (Tables 1-2) and opportunities for molded parts consolidations and design freedoms.

Unfilled and fiber-glass reinforced nylon (polyamide) based plastics are very efficient by mass reduction/“relative weight” (Tables 1-2), and in relative energy consumption (Table 2) for the production of various transportation and automotive components.

Nylon (polyamide) based plastics become a material of choice for North America and European transportation

⁵ Includes both materials and manufacturing

and auto-makers in lost-core molded and injection molded & vibration welded air intake manifolds (AIM). In replacing metal manifolds, fiber-glass reinforced thermoplastics have reduced part weight by as much as 65% (Figure 1).

Table 2. Energy and Weight Savings for Lightweight (LW) Materials and Automotive Plastic Parts [5]

LW Material	Relative Weight ⁶	Relative Energy Consumption ⁷
Mild steel	1	1
Aluminum	0.51	0.68
Unfilled Nylon 6	0.60	0.82
Unfilled Nylon 66	0.60	0.86
Unfilled PBT	0.72	0.87
Unfilled PP	0.65	0.79
30 wt.% GF Nylon 6	0.52	0.61
30 wt.% GF Nylon 66	0.52	0.67
30 wt.% GF PBT	0.56	0.54
30 wt.% GF PP	0.50	0.66



Figure 1. Linear Vibration Welded Air Intake Manifold (glass-fiber reinforced nylon/polyamide 6)

They also lower thermal conductivity, so car engines need not work as hard to produce power and torque. For many years, the automotive industry has consistently provided continuous growth opportunities for various plastics. Typically, the weight of a glass-fiber reinforced nylon-based automotive (or transportation) part is 40-55% less than a similar design made from stamped steel [4-8].

Under-the-hood nylon (polyamide) use in North America and Europe has grown from 87,500 tons to 165,000 in 1999 and is projected to be 230,000 tons in 2005. Today, approximately 25% of the materials used in the manufacture of European cars are thermoplastics. Reinforced/filled nylon (polyamide) has also become an

⁶ Weight to achieve a stiffness compared with steel (properties of steel = 1).

⁷ Total energy consumption for production and using an automotive component for 100.000 km for conditions described above for Relative Weight.

integral material in cooling components, valve covers, acoustic and cosmetic car engine covers, and various electrical connectors (flame-retardant grades). In design of the automotive powertrain parts, nylon is also a choice material for rocker covers, resonators, air cleaners, etc. (Figure 2).



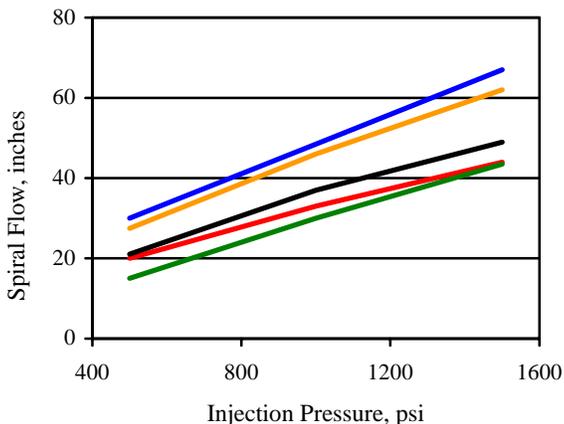
Figure 2. Linear Vibration Welded Resonator (glass-fiber reinforced and mineral filled nylon/polyamide 6)

SELECTION OF NYLON (POLYAMIDE) BASED PLASTICS FOR OPTIMIZED DESIGN AND ADVANCED PROCESSING TECHNOLOGY

When developing a new component, thermoplastic parts designers choose from a variety of fiber-reinforcements and resin systems. Knowledge of used materials properties is the first requirement for designing a safe and durable product. A well designed component that employed the right material and process to meet the application end-use requirements.

Fiber-glass (or fiber-carbon, etc.) reinforcements provide desired mechanical, physical properties. Comprehensive data and practical recommendations on various additives for nylon (polyamide) based thermoplastics are widely presented in [9-14]. Shear rate data for the HMG series plastics, shows lot of the advantages of HMG chemistry for highly reinforced (GF) thermoplastics.

Developed thermoplastics HMG series in (Figure 3) demonstrated viscosity close to that of standard unfilled nylon 6, and up to ~ 20% better flow under standard materials with comparable fiber-glass loading. The material retains the mechanical performance level of standard fiber-glass reinforced nylon (polyamide) while



reducing injection molding cycle time and improving surface appearance. Reduced viscosity reduces residual stresses and energy cost.

The special requirements of the industrial arena, including transportation and auto markets [3-6], appliances [7], etc. are influencing development of new types nylon (polyamides) based plastics, particularly high-flow grades that retain their high strength and stiffness (Young’s modulus), and high fatigue resi

Figure 3. Spiral Flow of High Modulus (HMG) an nylon (polyamide) 6 based plastics proces at optimum injection molding conditions. Legend - HMG10; 2 – unfilled; 3 – 33 wt.% GF; 4 - HMG13; 5 – 50 wt.% Long Fibers.

Three important *high modulus thermoplastic – molding tool – plastic part* interrelations must be considered at the outset by those specifying polyamide (nylon): nylon 6 is a family of related polymers/plastics, not a just a single composition [1, 8-11].



Figure 4. Car roof bike clamp (Capron® HMG13G colored in black).

Reinforced nylon plastics (with 15 – 40 wt.% fiber-glass reinforcements - GF) are commonly used in the design of automotive under-the-hood components, such as air intake manifolds (Figure 1), cooling fans and shrouds, fluid reservoirs, etc. [5].

The fiber-glass reinforced and mineral filled nylon plastics (25 – 45 wt.% GF/MF) are used in the design of door handles, shrouds, resonators (Figure 2) covers, etc. [5, 15]. High modulus/strength fiber-glass reinforced (with 45 – 65 wt. % GF) nylon (polyamides) are emerging in automotive structural body panels, levers, internal and external mirror housings, seat frames, steering wheels, and various heavily stressed door handles (Figures 4-6).

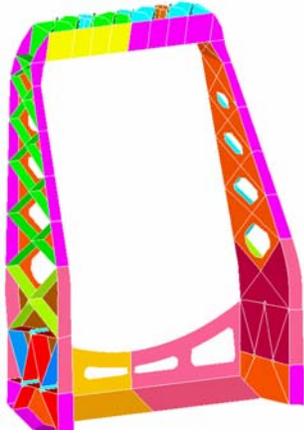


Figure 5. Example of structural analysis of auto seat frame (Capron® HMG13G).



Figure 7. Family of the automotive mirror brackets (Capron® HMG13G colored in black)

This family of fiber-glass reinforced or reinforced and filled plastics [8-10] can be considered, that all compositions have the following injection molding advantages for various transportation and automotive structural components and highly stressed solid and hollow parts:

- Good mechanical performance of the injection molded structural parts after several re-molding / re-grind cycles (mechanical property losses are minimal, etc.).
- Moldability to close tolerances.
- Fast overall processing cycles and ejectability (part release from molding tool) are very good.
- Predictable mold and annealing shrinkage. Small tendency for warpage.
- High flow and toughness in thin sections, easy to fill of complicated shapes of hollow parts.
- Sufficient knit line strength.
- Sufficient weld strength (at various welding technologies, such as vibration, orbital, hot plate infra-red/laser through-transmission, etc.).

While many development and research programs were oriented on the development on highly fiber-glass reinforced long-fibers nylon based plastics, a few studies concentrated on:

- High modulus materials (HMG) development with improved viscosity close to that of standard unfilled nylon.
- Selection of high modulus (HMG) nylon 6 based plastics for optimized design and advanced processing technology.

THE EFFECTS OF SHORT FIBER-GLASS REINFORCEMENT ON MECHANICAL PERFORMANCE OF NYLON (POLYAMIDES)

BASICS OF SHORT FIBER-GLASS REINFORCEMENTS OF THERMOPLASTICS: PROCESS ANALYSIS AND RESULTS

Fiber-glass is added to polymer (matrix) when it is necessary to improve (or reach needed parameters) their short-term and long-term mechanical properties. The reinforcing fiber-glasses (or fiber-carbon) may be short and long. Standard fiber-glasses are cylindrical, but it is possible to change a shape of the cross-section to oval, tri-lobular, etc. [13-14]. The level of reinforcement may vary for the type of reinforcements and applications [15]. A practical guideline for maximum loading of short fiber glass is 50 vol%⁸. In nylon (polyamide) based thermoplastics, the 50 vol.% fiber-glass loading corresponds to approximately 70 wt.% as a maximum loading of reinforcement, due to limitations of standard compounding techniques. Nylon (polyamide) powder coatings may use a multiplicity of particulate fillers (melt compounded) at high filler level up to 60 vol%.

The following key reinforcement (by fiber-glasses) variables (parameters) are more influential on mechanical properties of thermoplastics:

- Fiber-glass diameter - d_f .
- Average fiber-glass length - $L_{average}$.
- Aspect ratio r_f (at any phases of manufacturing, when the average fiber-glass length may be changed)

$$r_{f,average} = \frac{L_{f,average}}{d_f}$$

- Fiber-glass content (vol.% or wt.%).
- Fiber-glass surface state.

⁸ vol.% - level of reinforcement or filled by volume. Some authors are using the term "packing fraction" for this parameter.

- Fiber-glass mechanical performance (tensile strength - σ_f and tensile modulus - E_f).
- Coupling to the matrix (base resin).
- Fiber-glass orientation and distribution (through thickness) in highly loaded/stressed areas of injection molded part⁹.

Enhanced mechanical performance (tensile or flexural strength, rigidity/stiffness and fracture toughness) of fiber-glass reinforced thermoplastics is dependent on the optimum fiber-matrix interface design coupled to minimum attrition of glass filament length during a sequence of process steps. Inter-phase design is identified as the central gem affecting short fiber-glass thermoplastics mechanical properties over the service lifetime of an injection molded part [12-14, 16-19, 21-22]. It should be realized that it is quite difficult to mix fibers with polymer (matrix) during compounding and injection molding because of the exceptionally high viscosity of most polymers even at elevated temperatures.

During the manufacturing process (compounding, injection molding, etc.), fibers are involved in a lot of interaction with machinery. As a result, fibers length may be reduced dramatically. In order to minimize short fiber-glass damage (during processing) and maximize thermoplastic mechanical performance we need to optimize all phases of the manufacturing cycle (the compounding and injection molding).

The fiber-glasses for composites (thermoplastics and thermosets) are manufactured in the range of 8 μm to 25 μm . The diameter d_f of fiber-glass for nylon (polyamide) based plastics is generally 9-10 μm (but may vary). Some researcher observed an increase of tensile strength of GF reinforced nylon 66 for this diameter compared with 13 μm . Fiber-glass types, having a 13-14 μm diameter, are generally designed for PP based plastics. However, both tensile strength and fracture toughness for short fiber-glass reinforced polypropylene (PP) are improved by using the much smaller 9-10 μm diameter fiber [13]. Conversely, there is information that tensile and flexural strength are adversely affected by 17 μm size fibers.

Table 3. Influence of the Short Fiber-Glass Diameter d_f (E-glass) on Mechanical Performance of Fiber-Glass Reinforced Nylon 6,6 Based Plastics (30 wt.% GF).

Diameter of GF (in μm)	E10	E11	E14	E17
Tensile Strength, MPa	184	183	174	164
Tensile Modulus, GPa	9.73	9.76	9.55	9.50
Tensile Strains, %	2.83	2.80	2.70	2.49

⁹ Skin-core effects are very important for the parameters of flexural strength and stiffness, when stress-strain distribution through thickness isn't uniform.

Flexural Strength, MPa	287	285	270	249
Flexural Modulus, GPa	9.20	9.21	9.29	9.01
Un-notched Impact, J/m	979	894	775	568
Notched Impact, J/m	130	130	135	139

A wide evaluation of the influence of fiber-glass reinforcements on mechanical performance of injection molded nylon 6,6 (30 wt.% GF) are presented in this article [17]. The fibers with nominal diameters of 10, 11, 14 and 17 μm were used for this analysis (Tables 3-4). Nominal mechanical properties of used E and S-2 fiber-glass are shown in Table 3.

Table 4. Influence of the Short Fiber-Glass Diameter d_f (E-glass) on Mechanical Performance of Fiber-Glass Reinforced Nylon 6,6 Based Plastics (30 wt.% GF).

Diameter of Short Fiber-Glass - d_f , μm	$\frac{E17}{S2S}$	$\frac{E17}{S2S}$	$\frac{E17}{S2L}$
GF Composition ratio, %	95/5	80/20	80/20
Tensile Strength, MPa	164	173	174
Tensile Modulus, GPa	9.43	9.66	9.73
Tensile Strains, %	2.54	2.75	2.66
Flexural Strength, MPa	250	261	261
Flexural Modulus, GPa	8.75	9.14	8.69
Un-notched Impact, J/m	628	805	724
Notched Impact, J/m	136	134	137

The presented results show that the elastic properties of short fiber-glass reinforced nylon 6,6 (30 wt.% GF) are not strongly affected by the fiber-glass diameter in the 10 – 17 μm range. Elongation at break, tensile and flexural strength, and un-notched impact (Izod) all decreased by 5~10% over the 10 – 17 μm diameter range. Notched impact (Izod) showed a small increase over the same range. An addition of 20 wt.% of S-2 fiber-glass to the 17 μm E-glass resulted in a 8% improvement of the strength. Note: The tensile strength of combined fiber-glass composition by the fiber diameters (“E17”/”S2S”) is less than the tensile strength for “E11”fibers (182 MPa with 174 MPa).

A special study was conducted on the influence of a fiber-glass (with diameter 10 μm and 13 μm) on mechanical performance of glass reinforced (GF) and impact modified (IM) nylon 6 based plastics with the following compositions (Table 5):

- 25 wt.% GF + and 10 wt.% IM.
- 35 wt.% GF + 5 wt.% IM.

Table 5. Influence of the Fiber Diameter d_f on Mechanical Performance of Short Fiber-Glass Reinforced/Impact Modified Nylon 6 Based Plastics

Fiber-Glass Content, wt. %	25	25	35	35
Impact Modifiers, wt.%	10	10	5	5
Fiber diameter, μm	10	13	10	13
Tensile Strength, MPa	112	121	125	145
Flexural Strength, MPa	167	199	181	254

This study shows an increase of the tensile and flexural strength for fiber 13 μm diameter compared with 10 μm fiber diameter (for “K” size fibers). Increase of mechanical performance for the fiber 13 μm diameter compared with 10 μm fiber diameter is as follow:

- For tensile strength: ~ 8 - 20%.
- Flexural strength: ~ 19 - 40%.

These results are at variance with the data achieved for nylon 66 [17] and PP [9] based plastics and should be re-checked in the future. Due to observed discrepancies in published [8-9, 12, 17] and discussed above results on the influence of the diameter d_f on mechanical performance of nylon, we initiated additional investigation for highly reinforced (GF \geq 50 wt.%) nylon based thermoplastics (both HMG series).

Table 6. Influence of the Short Fiber-Glass Diameter d_f on Mechanical Performance of High Modulus (HMG) Fiber-Glass Reinforced Nylon 6 Based Plastics (50 wt.% GF)

Diameter of Fiber-Glass- d_f , μm	10	13	16
Tensile Strength, MPa	224	203	197
Flexural Strength, MPa	337	313	301
Flexural Modulus, Gpa	14.0	13.5	13.6
Un-notched Impact, J/m	1240	1016	947
Notched Impact,	133	121	129

For this investigation we used fiber-glasses with the following sizes (diameters d_f , in μm) of the fibers: 10; 13 and 16. Tables 6-7 shows the reinforcements effects for two nylon 6 based plastics HMG series with 50 wt.% GF and 63 wt.% correspondingly. The tensile strength and flexural strength decreases by \approx 18 – 20% when diameter of fibers d_f increases from 10 μm to 16 μm .

Notched impact data wasn't sensitive to the influence of d_f for both plastics. As the results of this investigation, for composition of HMG series plastics we used fiber-glasses with diameter equal 10 μm .

Table 7. Influence of the Short Fiber-Glass Diameter d_f on Mechanical Performance of High Modulus (HMG) Fiber-Glass Reinforced Nylon 6 Based Plastics (63 wt.% GF)

Diameter of Fiber-Glass- d_f , μm	10	13	16
Tensile Strength, MPa	248	232	223
Flexural Strength, MPa	407	346	337
Flexural Modulus, Gpa	19.1	17.7	18.0
Un-notched Impact, J/m	1230	1069	1016
Notched Impact, J/m	139	139	134

After a sequence of compounding and injection molding processes, the fiber-glass length is reduced from 3-5 mm to less than 0.45 mm for an average ($L_{average}$) depending on cumulative fiber-glass damage. This process highly dependent on fiber-glass content (vol.% or wt.%). Some of this is very interesting and helpful for the analysis result, which were presented in [9, 12, 14, 16 and 22].

The fiber-glass length (an average) $L_{average}$ is calculated by the following equation:

where:

$$L_{average} = k(t) \frac{d_f}{v_f}, \quad (1)$$

v_f - Fiber volume fraction (or in %).

d_f - Fiber diameter (in mm or μm).

$k(t)$ - Parameter (constant).

Shear loading forces act on the brittle fiber ends to cause a certain amount of fracture depending on v_f . This mechanical behavior limits the effective length $L_{effective}$ of fiber-glass to a minimum amount dictated this relationship. At low levels of fiber-glass loading (0-6 wt.%), the stress concentration at fiber-glass ends is quite high. The inherent brittleness is due to the relatively small fiber-glass diameter d_f . With little overlapping of the stress fields around fiber-glass in dilute medium, the notched Izod values are quite small.

At higher loading of fiber-glass, the thermoplastics become more ductile and exhibit corresponding increased notched impact values. By decreasing the mean fiber end spacing below a critical threshold value (six times the fiber diameter), the stress fields around individual fibers overlap strongly to modify the deformation characteristics of the polymer matrix. Therefore, a matrix toughening mechanism results from plasticity around fiber-glasses.

It is possible to predict the tensile strength σ_c of injection molded fiber-glass reinforced nylon based thermoplastics by the following equation:

$$\sigma_c = \frac{v_f \sigma_f}{(1 - L_c / 2L_{average}) C_o(t, RH)} + v_m \sigma_m(t), \quad (2)$$

where:

- $\sigma_m(t)$ is strength at yield of polymer (matrix) at temperature t , in MPa.
- $L_{average}$ - is average fiber-glass length, in mm or in μm .
- $C_o(t, RH\%)$ - is the orientation factor with the influence of temperature t and moisture (RH) effects. Value of C_o is in the following range:

$$1 \geq C_o(t, RH) \geq 0.3$$

The orientation parameter $C_o(T, RH)$ is equal to 1 for longitudinal (at flow direction) orientation (Figure 7).

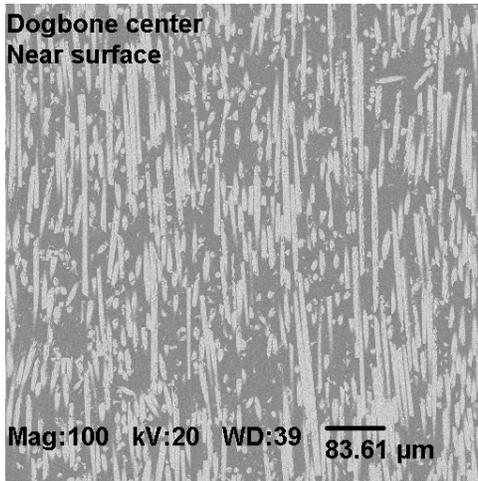


Figure 7. Fiber-glass orientation at central section of ISO specimens at plastic flow direction (Capron® HMG 13 HS, natural state)

The tensile strength at this direction reaches *maximum* value. For perpendicular to flow direction, this value may decrease by 30% - 50% (approximately) from the plastic strength at flow direction (at test temperature t and moisture in plastic).

The orientation of any single fiber may be calculated from its elliptical profile by the following equation:

$$\cos(\vartheta) = \frac{d_{\min or}}{d_{\text{major}}} = \frac{4A_{\text{ellipse}}}{d_{\text{major}}^2}, \quad (4)$$

where: ϑ - is the angle the fiber-glass axis makes with the melt-flow direction: $d_{\min or}$ - is the minor axis, $d_{\min or} = d_f$; d_{major} - is the ellipse major axis, and A - is the area of the ellipse. The $\cos(\vartheta)$ data is the key factor in calculation of the value of

orientation factor/parameter $C_o(t, RH\%)$. The details on methods of $C_o(t, RH\%)$ calculation with the influence of Weibull distribution of strength are presented in [19].

- L_c - is critical fiber length, in mm or in μm . The critical fiber length L_c may be determinate by the following equation:

$$L_c = \frac{d_f \sigma_f}{2\tau(t, RH)}, \quad (3)$$

where: $\tau(t, RH)$ - is the interfacial strength of polymer (matrix) with the influence of temperature t and moisture (RH) effects. The fiber length L distribution is a function $f(L)$ that may be determinate by the following equation (if $L > 0$):

$$f(L) = abL^{b-1} \exp(-aL^b), \quad (4)$$

where: a and b are scale and shape parameters respectively. The details on the estimation of average fiber-glass distribution are described in [20-21].

- σ_f - is effective fiber-glass strength, in MPa. The effective value of fiber-glass strength σ_f is equal (approximately) to half of the strength of continuous fiber-glass (Table 8). For continuous fiber-glasses the value of σ_f varied from 3.4 GPa (for E-type fiber-glass) to 5.9 GPa (for silica fibers).

The trends in mechanical properties of the fiber-glass reinforced injection molded nylon are as follow (Table 9):

- Tensile strength versus fiber-glass content is linear (in fiber-glass reinforcement range from 6 wt.% to 40-45 wt.% GF).
- Impact behavior increases with increased fiber-glass interaction due to higher v_f - vol.% (or wt%).
- There is a decrease in fiber-glass length from 4.7 mm to 0.4-0.2 mm (400-200 μm).
- The average of fiber-glass length is inversely related to fiber-glass loading (by volume or weight).

Table 8. Mechanical Properties of High Modulus Fiber-Glasses

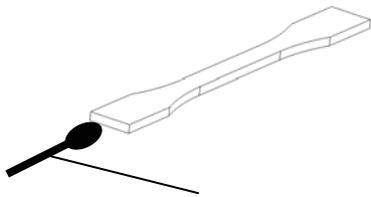
Material	Tensile Strength MPa	Tensile Modulus GPa	Specific Gravity
"A" fiber-glass	2.400	67	2.50
"C" fiber-glass	2.750	69	2.49
"D" fiber-glass	2.400	52	2.16
"E" fiber-glass	3.400	72	2.55

“ECR” fiber-glass	3.620	73	2.62
“R” fiber-glass	4.400	86	2.55
“S&S2” fiber-glass	4.820	87	2.49
Silica fibers	5.900	72	2.20
Hollow E-glass	1.400	50	2.00

Table 9. Influence of the Short Fiber-Glass Reinforcement on Fiber Length in Molded Thermoplastic

GF wt %	GF vol. %	Fiber Length μm	Constant k	Tensile Strength MPa
0	0	0	0	82
10	0.048	436	0.216	104
20	0.101	337	0.351	140
30	0.181	261	0.457	177
45	0.230	225	0.422	198
50-HMG	0.309	201	0.663	262
63-HMG	0.44	188	0.768	280

The fiber-glass length and diameters were evaluated by image analysis and optical microscopy on fiber-glass samples extracted from the injection molded (short-fibers and long-fibers) multipurpose ISO specimens (Figure 8) after high-temperature ashing.



Gate system for long-fiber nylon 6

Figure 8. Injection molding of long-fibers one side specially (improved molding tool design) gated ISO multipurpose test specimen.

Measurements of fiber-glass orientation parameter $C_o(T, RH)$ was performed on the cross-sections of a these multi-purpose ISO specimens machined perpendicular to the melt-flow direction.

At elevated temperature conditions, the influence of reinforcement is a more critical factor than at room temperature, due to possible changes in mechanical and viscoelastic properties of polymer (matrix). For high levels of reinforcements ($GF \geq 50$ wt.%), the critical

aspect ratio $(\frac{L_c}{d_f})$ is 20:1 approximately.

The levels of reinforcement are in the range of 20 wt.% ~ 30 wt.%; this ratio is 35 (28):1 (Table 9). Based on theoretical assumption presented in [9 and 18], the

strengthening effects of fiber-glass reinforcement increase with aspect ratio $(\frac{L_c}{d_f})$ asymptotically is

reaching a limit close of 400:1. This ratio is more typical for highly loaded long-fibers reinforcement conditions. The results presented in Table 7 are in disagreement with these assumptions, because for high levels of reinforcements ($GF \geq 50$ wt.%) an increase of mechanical performance was achieved at lowest levels of the aspect ratio. The tensile strength of injection molded nylon 6, increases linearly with the fiber-glass content up to 40 - 45 wt.%. Following the increase of fiber-glass content of 45 – 50 wt.%, the tensile strength then asymptotically is reaching a limit of *maximum* in the mechanical performance and *maximum* in loading (packing) of fiber-glass reinforcements.

BASIC MECHANICAL PROPERTIES NEEDED FOR DESIGNING WITH HIGH MODULUS (HMG) FIBER-GLASS REINFORCED NYLON (POLYAMIDES)

The basic mechanical properties needed for designing with high modulus/strength (HMG) nylon based plastics should be developed with the influence of part design, end-use conditions and processing technology features. Mechanical test results need to be conducted at various end-use environmental and mechanical loading conditions, typical for end-use applications. The following base/key mechanical and tribological properties of materials are very important for designing with high modulus (HMG series) plastics:

- Short-term properties.
- Long-term properties.
- Tribological properties and molded part/specimen appearance (state of molded surface).

Short-term mechanical performance of high modulus thermoplastics is important for quality control to ensure the constant properties of raw materials and injection molded parts.

Long-term properties of engineering thermoplastics are more important in predicting the service time of the various injection molded parts with the influence of time-temperature effects: creep, fatigue and repeatable impact.

EXPERIMENTAL: USED PLASTICS, SPECIMENS, INJECTION MOLDING AND TEST CONDITIONS

The following thermoplastics analyzed in this investigation were nylon (polyamide) 6 based thermoplastics (short and long) fiber-glass reinforced (all heat stabilized series - HS):

- 63 wt.% short fiber-glass reinforced HM series plastic (Capron® HMG13G HS).

- 50 wt.% short fiber-glass reinforced HM series plastic (Capron® HMG10G HS).
- 50 wt.% short fiber-glass reinforced plastic, traditional chemistry (Capron® 8235G HS).
- Non-reinforced plastic, traditional chemistry (Capron® 8202 HS).
- 50 wt.% long fiber-glass reinforced commercial available plastic.

These thermoplastics were injection molded into the following standard specimens:

- ISO multipurpose tensile specimens (ISO 3167¹⁰). Injection molded ISO 3167 specimens were used for development of the tensile, compressive, flexural, impact (notched and un-notched) and creep data.
- ASTM D-677 (flexural fatigue specimens).
- ASTM D-3763 (instrumented impact data).
- ASTM D-638 (type 1, both sides gated specimens for knit-line data).
- Rectangle plaques (150 mm x 50 mm x 6 mm and 150 mm x 50 mm x 4 mm) for the weldability data (vibration and hot plate welding).

Special attention was focused on to the molding of long-fiber nylon 6 (Figure 9). Prior to injection molding, nylon (polyamide) pellets were dried by ASTM/ISO requirements. ISO (or ASTM, type 1) multipurpose specimens were injection molded using the standard practice (ISO 294-1, ISO 294-2, ASTM D 3641 and ASTM D 4066) and published recommendations for processing parameters [9-11].

After injection molding, all specimens were sealed (see ASTM D 3892) prior to testing and evaluation in order to maintain their dry-as-molded (DAM) conditions¹¹.

All basic mechanical performance related evaluations were performed in air at relative humidity of 50% at 23°C. The static tensile tests were conducted according ISO 527 (ASTM D 638), using an Instron Universal Tester (Model 4505) with an environmental test chamber, at cross-head speed of 50mm/min (Capron® 8202 HS is an unfilled plastic) and temperatures of -40, 23 and 150°C (± 1°C).

Cooling and heating in the chamber was provided using liquid nitrogen and electrical heating respectively. Five tensile specimens were tested at every injection molding conditions.

SHORT-TERM MECHANICAL PROPERTIES

The following short-term properties of high modulus (HMG) thermoplastics are important for plastic parts design, design analysis & optimization:

- Tensile (strength at yield, strength at break, strain at break, tensile modulus, Poisson’s ratio).
- Compressive (strength, Young modulus).
- Shear (shear strength).
- Flexural (strength at break, strain at break, “flexural” modulus).
- Resistance to Fracture (impact – un-notched, notched, instrumental impact).
- Fracture Mechanics (fracture toughness, stress release energy).

Table 10. Short - Term (Static) Properties of Capron® HMG Series Nylon 6 Based Plastics (all HS – Heat Resistance Package. At 23°C, Dry-as Molded, DAM. Color Version: Natural State).

Short-Term Mechanical Properties (DAM)	HMG 10G	HMG 13G	Long Fiber
Type of Reinforcement	short	short	long
Fiber-Glass Content, wt.%	50	63	50
Density, gm/ cm ³	1.56	1.74	1.56
Tensile Strength, MPa	262	280	248
Young Modulus , GPa	17.4	22.4	17.2
Ultimate Elongation, %	2.72	2.27	2.11
Flexural Modulus, GPa	13.8	18.5	15.2
Flexural Strength, MPa	326	370	365
Compressive Strength, MPa	234	262	228
Compressive Modulus at 3% Strains, GPa	20.2	20.8	20.3

The basic short-term static properties of two HMG series (50 wt.% GF and 63 wt.% GF) and long-fiber (50 wt.% GF) are presented in Table 10. The tensile strength of fiber-glass reinforced nylon increases continuously at all ranges of analyses ranging from 6 wt.% GF to 63 wt.%GF (see Tables 10 and 12).

The influence of temperature effects (from - 40°C to 150°C) on mechanical performance of 63 wt.% nylon (polyamide) 6 HMG series plastic is shown in Figure 9. Table 11 shows dynamic short-term properties of these thermoplastics. With the fiber-glass content increased, the tensile and flexural strength are increasing also. Static short-term mechanical performance of long-fiber plastic is very similar to short fiber-glass plastic HMG series (with the same level of wt.% GF). Some differences were observed for notched impact data only.

¹⁰ It is possible to use ASTM D 638 type 1 specimens for multipurpose test also.

¹¹ ASTM D 4066 specification for moisture content (wt.% max) in “as received” nylon/polyamide 6 is 0.2%.

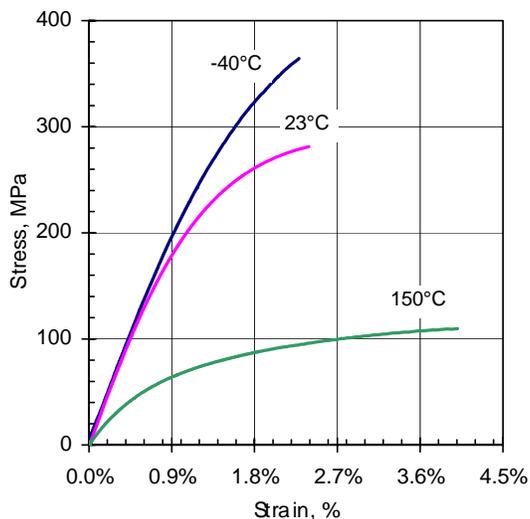


Figure 9. Influence of temperature effects on mechanical behavior (stress-strain curve) of HMG series nylon 6 based plastic (short fiber-glass reinforcement, 63 wt.% GF). Legend: material state: DAM, color - natural state.

Table 11 shows dynamic short-term properties of these thermoplastics. With the fiber-glass content increased, the tensile and flexural strength are increasing also. Static short-term mechanical performance of long-fiber plastic is very similar to short fiber-glass plastic HMG series (with the same level of wt.% GF). Some differences were observed for notched impact data only.

Table 11. Short - Term (dynamic) Properties of Capron® HMG Series Nylon 6 Based Plastics (all HS – Heat Resistance Package. At 23°C, Dry-as Molded, DAM. Color Version: Natural State).

Short-Term Dynamic Mechanical Properties	HMG 10G	HMG 13G	Long Fiber
Notched Izod, J/m	12.4	13.5	32.4
Un-notched, J/m	71.3	67.5	77.4
Instrumented Impact/Energy at Failure, J	18.5	19.5	17.4

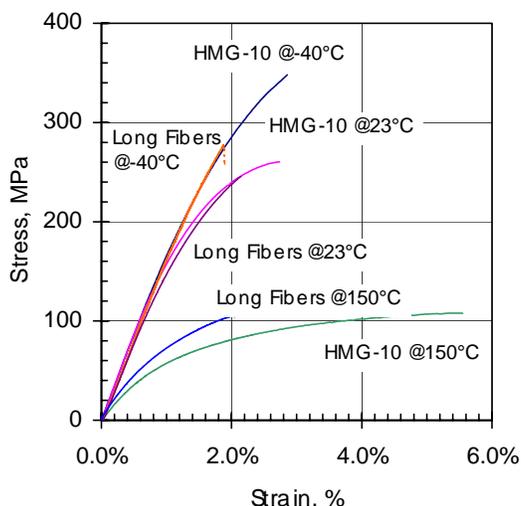


Figure 10 presents the tensile properties comparison between long fiber-glass nylon (polyamide) 6 and HMG series thermoplastic (both are 50 wt.% GF) with the influence of temperature effects (from - 40°C to 150°C).

At room and elevated temperatures, the tensile strength of both plastics is approximately similar. Long fiber nylon 6 is more brittle at this range of test temperatures and less by strength at - 40°C also (Figure 11).

Figure 10. Influence of temperature effects and reinforcement type (short fiber-glass with long fibers) on mechanical behavior (stress-strain curve) of 50 wt.% nylon 6 based plastics. Legend: material state: DAM, color - natural state. HMG10G (short fiber-glass reinforcement). Long Fibers (long fiber-glass reinforcement).

LONG-TERM MECHANICAL PROPERTIES

The following long-term properties of high modulus (HMG) thermoplastics are important for plastic parts design, design analysis & optimization:

- Creep (at tensile and flexural loading conditions: creep modulus, creep rupture strength, isochronous stress-strain creep curves at various temperatures).
- Stress relaxation (at compressive loading conditions) data at various temperatures and strains.
- Fatigue (at tensile-tensile and flexural loading conditions, S – N curves, fatigue cracks propagation data) resistance at various temperatures.

HMG series plastics have improved resistance to creep (Figure 11) and fatigue (Figure 12) with the influence of various temperatures (23°C and 150°C) when compared with similar fiber-glass loaded grades of conventional nylon 6.

TRIBOLOGICAL PROPERTIES

The following tribological properties of high modulus (HMG) nylon (polyamide) 6 based thermoplastics are important for plastic parts design, design analysis & optimization:

- Wear factor
- Coefficient of friction.

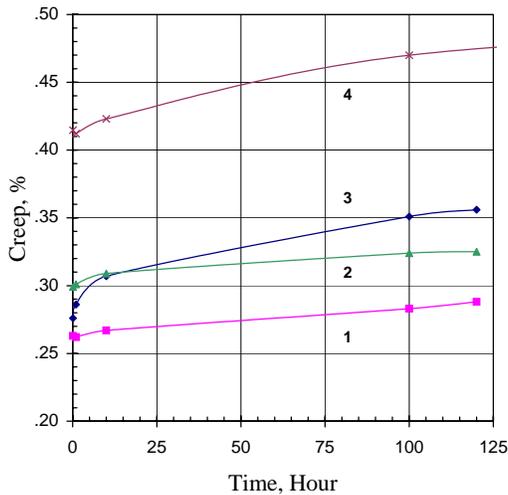


Figure 11. Influence of reinforcement type (short fiber-glass with long fibers) on resistance to tensile creep of nylon 6 based plastics. Legend: material state: DAM, color - natural state; Test temperature - 23°C; 1 - HMG13 (63 wt.% GF); 2 - HMG10 (50 wt.% GF); 4 - long fiber-glass (50 wt.% GF); 4 - 33 wt.% GF.

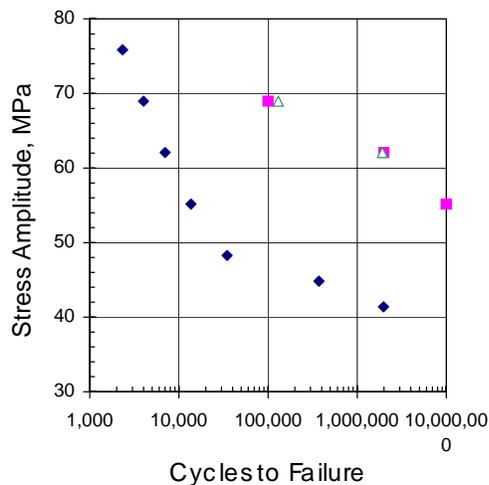


Figure 12. Advantages of HMG based plastics for the design of cyclically stressed components. Legend: \square - HMG plastics; 63 wt.% GF, \square - 33 wt.% GF.; Materials state - DAM at tests start, color - natural state.

Fiber-glass reinforcements often leads to an increase in coefficient of friction and mating surface wear. Previously developed highly reinforced (traditional chemistry) plastics had tendency to have fiber-glass interspersed within a matrix, resulting in rough surface appearance. The chemistry of HMG grades thermoplastics allows the melt to flow faster and wet-out the fiber-glass reinforcements better, resulting in a higher gloss and improved finish.

Average of coefficients of friction (no additional lubricants) of Capron® HMG series plastics are as follow:

- Static - 0.24
- Dynamic - 0.26.

TECHNOLOGICAL ADVANTAGES OF HMG PLASTICS: MECHANICAL PERFORMANCE AT KNIT-LINE AND WELD-LINE AREAS (INTER-PHASES)

Tensile strength of knit and weld lines are critically important for the plastic selection for various transportation and automotive applications where injection molded and welded parts will be stress-strain bearing. The knit and weld lines (planes) are created wherever polymer flow's front meet from opposite or parallel directions correspondingly (Figure 14 and 15).

These lines (planes)¹² are significant for injection molded and subsequent welded thermoplastic part performance because the local mechanical properties in the knit, meld and weld lines/planes areas differ significantly from those in the rest (total/bulk) areas of the molded parts.

In general, process of development of the weld lines is very similar to knit lines (Figure 13) formation when melt flows are coming from two opposite located gates. During the welding of thermoplastics, two uniform (by geometry) melt flows will develop and meet at weld plane area and will create the weld inter-phase.

As an example for weld line formation, we will use the frictional method of welding. By geometry (shape and sizes), the weld lines are very similar to knit lines. The sizes of the weld lines depend upon the design of the welded beads. By its length, weld lines are very long (up to 2 m and more) and are equal to the length of contour l of the welded part(s). The thickness t of the weld line(s) is equal to the thickness of the narrow part of the weld bead.

Table 12 shows the influence of fiber-glass reinforcement (from 0 to 63 wt.%) on the tensile strength at knit and weld lines for nylon 6 based plastics. Both results are very similar, and they are very close to tensile strength of non-reinforced plastic (base polymer).

High modulus (HMG) short fiber-glass reinforced nylons have the tensile strength at knit and weld lines, which are different (significantly less) from the tensile strength of reinforced/filled plastic due to flow patterns and local

¹² In the mechanical performance and morphology analysis, we will use the term "inter-phase" also as the three dimensional description of this very complicated by glass-fibers and polymer chains re-orientation areas [10-11].

fiber-glass re-orientation at knit and weld lines (inter-phases).

Table 12. Influence Of Fiber-Glass Reinforcement On The Tensile Strength (At 23°C, Dry As Molded) Of Knit and Weld Lines (Nylon 6 Based Plastics. Optimized Processing Conditions)

Wt. %, GF	Tensile Strength of Plastic (MPa)	Tensile Strength of Knit Line (MPa)	Tensile Strength of Weld Line (MPa)
0	82	81.5	81
6	85	83.5	83.1
14	125	89.1	90.7
25	160	87.5	90.2
33	185	89.2	85.6
45	208	83.3	82.1
50 (HMG)	262	83.3	83.2
63 (HMG)	280	83.8	83.4

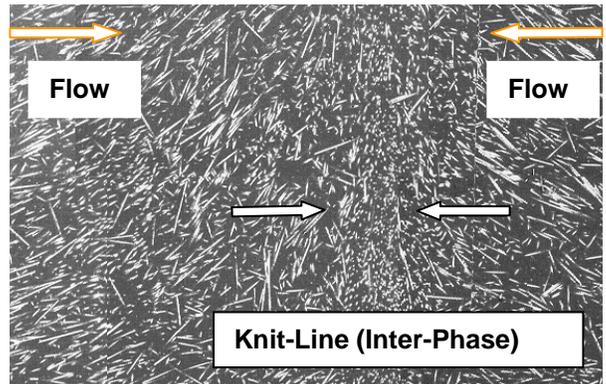


Figure 13. Example of fiber-glass orientation at knit-line (inter-phase) area in injection molded doubled gated multipurpose ISO 3167 specimen (Capron® HMG10G).

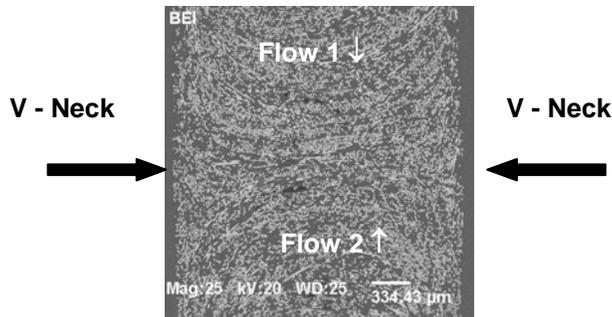


Figure 14. Example of knit-line (inter-phase) formation in injection molded part (Capron® HMG13G).

At the same time for HMG series plastics, the tensile strength at knit and weld lines remains the same as for non-reinforced plastics or slightly higher, than the tensile strength of used resin (matrix).

Due to the specifics of the weld-line formation, the tensile strength of the weld for long fiber-glass material is less than for short fiber-glass nylon 6 based plastics with the same loading of fiber-glasses (Table 13).

Table 13. Mechanical Performance of Vibration Welded Short (HM Series) and Long Fiber-Glass Nylon 6 Based Thermoplastics.

Material	wt.% GF	Type of GF	Tensile Strength of Weld, MPa
HMG10G	50	short	83.2
HMG13G	63	short	83.4
Long fiber-glass	50	long	53.7

CURRENT AND POTENTIAL APPLICATIONS

When developing a new part, thermoplastic parts designers chose from a variety of fiber reinforcements and resin systems. Knowledge of material properties with the influence of processing technology and end-use conditions is the first requirement for designing the safe parts and assembled products.

HMG grades will include 50 wt.% and 63 wt.% fiber-glass reinforced thermoplastics colored in natural, several types of carbon black and various custom colors. Injection molded Capron® HMG components have remarkable high modulus, tensile and flexural strength, fatigue, and creep resistance.

In automotive applications, these plastics may be used in design of electrical battery supports, clutch pedals,

clutch master cylinders, gear shifts, cable housings, wire harnesses, door handles and door lock mechanisms.

Some examples of the automotive applications experimentally molded from HMG series plastics are:

- Car roof bike clamp (Figure 4).
- Auto seat frame (Figure 5).
- Fuel filter lead.
- Brackets of automotive external mirror (Figure 6).

Other non-transportation industrial applications, includes various structural components, wheels, levers, housings, clamps system (Figure 15), sport equipment (Figure 16) and electrical (Figure 17) components.

Attachment 1 shows comparison in the mechanical properties of HMG series plastics and long fiber grade (50 wt.% GF) with the influence of temperature (from -40°C to 150°C). The guide for materials pre-selection by “relative performance” shows the advantages of HMG series grades (Attachment 2).



Figure 15. An example of injection molded J-bar clamp system for appliances (Capron® HMG13G, natural color).



Figure 16. An example of injection molded sport equipment personal transportation part (ski binding, Capron® HMG13G colored in black).

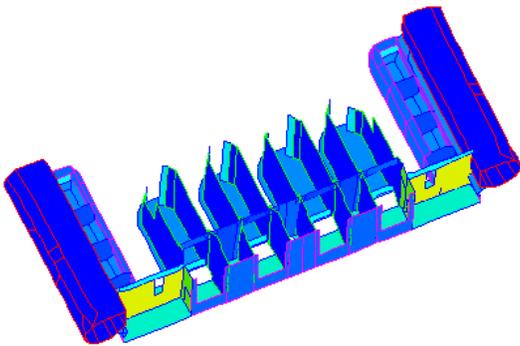


Figure 18. MoldFlow® analysis of the electrical connector (Capron® HMG13G).

CONCLUDING REMARKS

- High modulus (HMG) short fiber-glass nylon (polyamide) 6 based reinforced plastics may replace high performance thermoplastic products, such as polyarylamide, polyphenylene sulfide, and polyphthalamide.
- Short-term (stiffness, strength, etc.) and long-term mechanical properties of HMG series of plastics are similar to the above discussed thermoplastics, but the new HMG grades will cost less and be easier to process. Their flow characteristics provide processing advantages including faster cycle time, fewer injection points on large plastic components, smaller runners and less scrap compared to standard grades of fiber-glass reinforced nylon.
- These HMG series nylon (polyamide) 6 grades can compete with the long-fiber thermoplastics without processing and performance difficulties.

ACKNOWLEDGMENTS

The authors wish to thank Robert Sanchez for injection molding, John Fleming, Igor Palley, and Steve Preziosi for testing, Jeff Kipnis for the developed images for fiber-glass orientation. Special thanks goes to Scott Craig, Lynn Griffin, Nanying Jia, Mario Lambi and Christopher Rorh for help in preparing this study for publishing. Their contributions are greatly appreciated.

REFERENCES

1. Zachariades, A. and Porter, R., "High Modulus Polymers: Approches to Design and development", Marcel Dekker, Inc., 517 pages, New York – Basel, 1988.
2. "FRP Materials, Manufacturing Methods and Markets - Overview", Composites Technology, July, pp. 6-20, 2000.
3. "New Plastics and the Automobile", Automotive Engineering International, May, pp. 71-89, 2000.
4. Graff, G., "Autos, Electronics Ignite Development of New Polyamides", Modern Plastics, April, pp. 52-55, 2000.
5. Powers, W. F., "Automotive Materials in the 21-th Century", Advanced Materials & Processes, May, pp. 38-41, 2000.
6. Hauck, C. and Ramlow, G., "Auto Modules will Play to Plastic's Strength", Modern Plastics, January, pp. 70-72, 2000.
7. Tewari, G., "The Plastics Renaissance", Appliance, August, pp. 63-69, 2000.
8. "Capron® Nylon Typical Properties Charts", BASF Corporation, Engineered Applications & Solutions, Morristown, New Jersey, 14 pages, 1998.
9. Kohan, M., "Nylon Plastic Handbook", Hanser/Gardner Publications, Inc., New York, 598 pages, 1997.
10. "Plastics Handbook" Vol. 4, Polyamide, Hanser Publishing, Munich, 905 pages, 1998.
11. "Engineering Plastics", Engineered Materials Handbook, Vol. 2, ASM International, Metals Park OH, 882 pages, 1988.
12. Pritchard, G., "Plastics Additives: An A-Z Reference", Charman & Hall, London-New York, 663 pages, 1998.
13. Gachter, R., Muller, H., "Plastic Additives Handbook: Stabilizers, Proceeding Aids, Plasticizers, Fillers, Reinforcements, Colorants for Thermoplastics", 4-th Editions, 675 pages, Hanser Publishers, Munich-Vienna-New York, 1991.
14. Holister, G., S., "Fibre Reinforced Materials", Elsevier Publishing Co. Ltd., Amsterdam-London- New York, 154 pages, 1966.
15. Maxwell, J., "Plastics in the Automotive Industry", 189 pages, Woodhead Publishing Limited, Cambridge, UK, 1998.
16. Shiao, M.-L., "The Role of Matrices and Glass Fiber on the Deformation and Fracture of Short Glass Fiber Reinforced Thermoplastics", Ph.D. Dissertation Thesis, Univ. of Massachusetts, 1993.
17. Thomason, J., L., "The Influence of Fibre Properties of the Performance of Glass-Fiber-Reinforced Polyamide 6,6", Composites Science and Technology, Vol. 59, pp. 2315-2328, Elsevier Science, Ltd., New York, 1999.
18. Lunt, J., M., CDC Conference, London, October, 1980.
19. Lauke, B., and Fu, S.-Y., "Strength Anisotropy of Misaligned Short Fibre-Reinforced Polymers", Composites Science and Technology, Vol. 59, pp. 699-708, Elsevier Science, Ltd, New York, 1999.
20. Harper, C., A., "Handbook of Plastics, Elastomers, and Composites", McGraw-Hill Co., 3-rd Edition, 898 pages, New York, 1998.

21. Zak, G., Haberer, M., Park, C., B., and Benhabib, B., "Estimation of Average Fibre Length in Short -Fibre Composites by Two-Section Method", Composites Science and Technology, Vol. 60, pp. 1763-1772, Elsevier Science, Ltd, New York, 2000.
22. Jones F. Roger, "Guide to Short Fiber Reinforced Plastics", 174 pages, Hanser Publishers, Munich-Vienna-New York, 1998.

KEY WORDS

Nylon, polyamide, injection molding, reinforcement, fiber-glass, short, long, size, performance, mechanical properties, strength, strains, elongation, modulus, fatigue life, creep, weight savings.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

AIM: Air intake manifold

ASTM: American Society of Testing and Materials

BK: carbon black

DAM: dry as molded

GF: fiber-glass reinforcement

$L_{average}$ - average fiber-glass length, in mm or in μm

σ_f - tensile strength of the fiber-glass

$\sigma_m(t)$ - tensile strength of polymer (matrix) at temperature t

ISO: International Organization for Standardization

MF: mineral filled

PA: polyamide

PP: polypropylene

RH: relative humidity

SAE: The Engineering Society for Advancing Mobility Land Sea Air and Space

SEM: scanning electron microscopy

$C_o(t, RH\%)$ - orientation factor with the influence of moisture and temperature effects

d_f - fiber-glass diameter

E – Young's modulus of the plastic

E_f - Young's modulus of the fiber-glass

e – strain

ρ - density of the plastic, gm/cm^3

wt. - level of plastic reinforcement (or filled) by weight in %

Attachment 1. Material Pre-Selection Guide: Mechanical Performance of HMG series Nylon 6 Based Plastics with the Influence of Moisture and Test Temperature (from -40 °C to 150 °C. Color Version: Natural State).

Mechanical Property	Test Temperature, °C	HMG10G	HMG10G	HMG13G	HMG13G	Long Fibers	Long Fibers
Plastic State Prior to Test		DAM	50%RH	DAM	50%RH	DAM	50%RH
Type of Reinforcement		short	short	short	short	long	long
Reinforcement, wt.%		50	50	63	63	50	50
Density, gm/cm ³		1.56	1.56	1.74	1.74	1.56	1.56
Tensile Strength, MPa	- 40	342	323	367	367	274	283
	23	262	181	281	199	248	169
	150	110	83	112	84	109	83
Strain at Break, %	- 40	2.78	2.67	2.29	2.35	1.77	1.97
	23	2.72	4.24	2.27	3.43	2.11	2.41
	150	5.50	4.05	3.91	3.22	2.10	1.86
Young's Modulus, GPa	- 40	17.2	18.2	23.2	24.7	17.2	18.7
	23	17.5	12.1	22.3	16.4	17.2	12.2
	150	7.9	7.3	10.2	8.7	9.7	8.2

Attachment 2. Material Pre-Selection Guide: Relative Mechanical Performance of HMG series Nylon 6 Based Plastics with the Influence of Moisture at Room Temperature (23°C). Color Version: Natural State.

Mechanical Property	Test Temperature, °C	HMG10G	HMG10G	HMG13G	HMG13G	Long Fibers	Long Fibers
Plastic State Prior to Test	DAM / 50%RH	DAM	50%RH	DAM	50%RH	DAM	50%RH
Type of Reinforcement	Short / Long	short	short	short	short	long	long
Reinforcement, wt.%		50	50	63	63	50	50
Density, gm/cm ³		1.56	1.56	1.74	1.74	1.56	1.56
Tensile Strength, MPa	23	262	181	281	199	248	169
Relative Tensile Strength ¹³	23	168	116	162	114	159	108
Young's Modulus, GPa	23	17.5	12.1	22.3	16.4	17.2	12.2
Relative Young's Modulus ¹⁴	23	11.2	7.76	12.8	9.42	11.0	7.82

¹³ Relative Tensile Strength = Tensile Strength at Break/Density.

¹⁴ Relative Young's Modulus = Young's Modulus/Density.

Copyright © 2001 Society of Automotive Engineers, Inc.

Capron® is a registered trademark of BASF Corporation
Copyright BASF Corporation 2003

This information is provided for your guidance only. We urge you to make all tests you deem appropriate prior to use. No warranties, either expressed or implied, including warranties of merchantability or fitness for a particular purpose, are made regarding products described or information set forth, or that such products or information may be used without infringing patents of others.

BASF Corporation
3000 Continental Drive - North
Mount Olive, New Jersey 07828-1234

www.basf.com/usa
www.plasticsportal.com

©Copyright BASF Corporation 2003

HELPING MAKE PRODUCTS BETTER™

BASF