

AN ADVANCED HIGH MODULUS (HMG) SHORT GLASS-FIBER REINFORCED NYLON 6: PART II - MECHANICAL PERFORMANCE

Abstract

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

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.

In Part I of this paper, we presented results on the role and kinetic of reinforcement with the influence of level of loading and geometrical parameters of used fiber-glass. In Part II of this paper, we are presenting results on short-term and long-term mechanical performance of developed high modulus reinforced plastics.

Introduction

Knowledge of developed materials properties is the first requirement for designing a safe and durable thermoplastic product. The key mechanical properties needed for designing with high modulus/strength (HMG) nylon should be developed with the influence of part design, end-use conditions and processing technology features [1-2]. Mechanical test results need to be conducted at various 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 (HMG) 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 molded parts with the influence of time-temperature effects: creep, fatigue and repeatable impact.

Experimental

Plastics, Specimens, Molding and Test Conditions

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

- 63 wt.% short fiber-glass reinforced Ultramid® HMG series plastic.
- 50 wt.% short fiber-glass reinforced HMG series plastic and 50 wt.% short fiber-glass reinforced, traditional chemistry commercially available plastic.
- Non-reinforced, traditional chemistry commercially available plastic.
- 50 wt.% long fiber-glass reinforced commercially available plastic.

These thermoplastics were injection molded into the following standard specimens:

- ISO multipurpose tensile specimens (ISO 3167¹). These 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.

Special attention was focused on the molding of long-fiber nylon 6. Prior to injection molding, nylon pellets were dried by ASTM/ISO requirements. ISO (or

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

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 [3-6]. 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) conditions².

All basic mechanical performance 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, and temperatures of -40, 23 and 150°C ($\pm 1^\circ\text{C}$). 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 Properties

The following short-term properties of high modulus (HMG) thermoplastics are important for plastic parts design, design analysis & optimization [5, 7]:

- 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).

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 Tables 1-2. The tensile strength of fiber-glass reinforced nylon increases continuously at all ranges of analyses ranging from 6 wt.% GF to 63 wt.% GF. The influence of temperature effects (from - 40°C to 150°C) on mechanical performance of 63 wt.% nylon 6 HMG series plastic is shown in Figures 1-2. Table 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 "relative³ performance" shows the advantages of HMG series grades (Table 2).

² ASTM D 4066 specification for moisture content (*wt.% max*) in "as received" nylon/polyamide 6 is 0.2%.

³ Relative Tensile Strength = Tensile Strength at Break/Density. Relative Young's Modulus = Young's Modulus/Density.

Table 3 shows dynamic (impact) short-term properties of HMG series 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.

Figure 2 presents the tensile properties comparison between long fiber-glass nylon 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 essentially the same. Long fiber nylon 6 is more brittle at this range of test temperatures and lower strength at -40°C also.

Long-Term Properties

The following long-term properties of high modulus (HMG) thermoplastics are important for material development and 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 3) and fatigue (Figure 4) over a range .. 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 (HM) thermoplastics are important for plastic parts design, design analysis & optimization:

- Wear factor
- Coefficient of friction.

Fiber-glass reinforcements often leads to an increase in coefficient of friction and mating surface wear. Previously developed highly reinforced (traditional chemistry) plastics has the 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 Ultramid® HMG series plastics are as follow:

- Static - 0.24
- Dynamic – 0.26.

Performance of HMG Plastics 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 industrial applications where 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. These lines (planes)⁴ are significant for injection molded and subsequent welded thermoplastic part performance because the local mechanical properties in the knit, weld 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 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 4 shows the influence of fiber-glass reinforcement (0; 50 and 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 fiber-glass re-orientation at knit and weld lines (inter-phases).

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 4).

Concluding Remarks

High modulus (HMG) short fiber-glass 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 HM series of plastics are similar to the above discussed thermoplastics, but the new HMG grades will cost less and be easier to process. These grades can compete with the long-fiber thermoplastics without processing and performance difficulties.

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⁴ 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].

Table 1. Short-Term Mechanical Performance of HMG series Nylon 6 Based Plastics

Mechanical Property	Test Temp., °C	HMG10	HMG10	HMG13	HMG13	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, g/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
Flexural Strength, MPa	23	326		370		365	
Flexural Modulus, GPa	23	13.8		18.5		15.2	
Compressive Strength, MPa	23	234		262		228	
Compressive Modulus at 3% Strain, GPa	23	20.2		20.8		20.3	

Table 2. Relative Mechanical Performance of Ultramid® HMG series Nylon 6 Based Plastics

Mechanical Property	Test Temp., °C	HM10G	HM10G	HM13G	HM13G	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, g/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	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	23	11.2	7.76	12.8	9.42	11.0	7.82

Table 3. Short - Term (dynamic) Properties of Ultramid® HM 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	HM G10	HM G13	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

Table 4. 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	85.5	81
50 (HMG)	262	83.3	83.2
50 (long fib.)	248	78.5	53.7
63 (HMG)	280	83.8	83.4

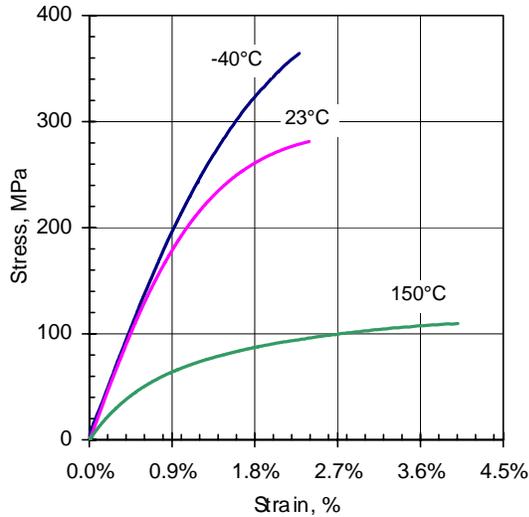


Figure 1. Influence of temperature effects on mechanical behavior (stress-strain curve) of HMG series nylon 6 based plastic (short fiber-glass reinforcement, 63 wt.% GF). Legend: material state: DAM, color - natural state.

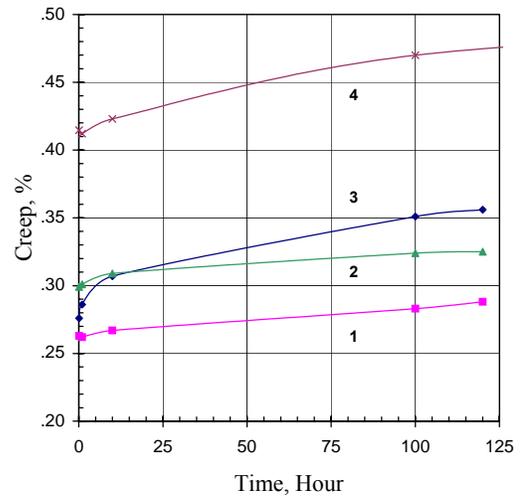


Figure 3. Influence of reinforcement type (short fiber-glass with long fibers) on resistance to tensile creep of nylon 6 based plastics. Legend: material state: DAM, color - natural state; Test temperature - 23°C; 1 - HMG13 (63 wt.% GF); 2 - HMG10 (50 wt.% GF); 4 - long fiber-glass (50 wt.% GF); 4 - 33 wt.% GF.

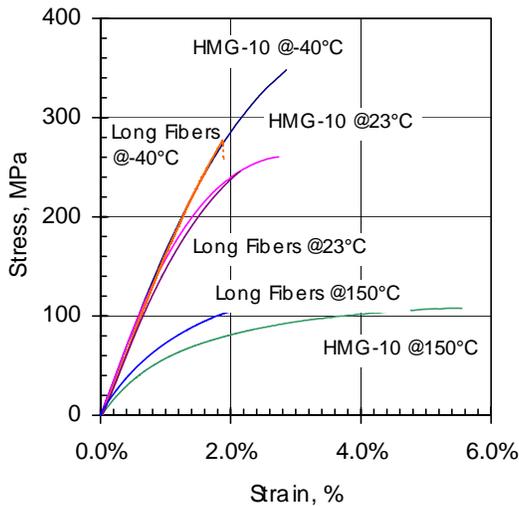


Figure 2. Influence of temperature effects and reinforcement type (short fiber-glass with long fibers) on mechanical behavior (stress-strain curve) of 50 wt.% nylon 6 based plastics. Legend: material state: DAM, color - natural state. HMG10 (short fiber-glass reinforcement). Long Fibers (long fiber-glass reinforcement).

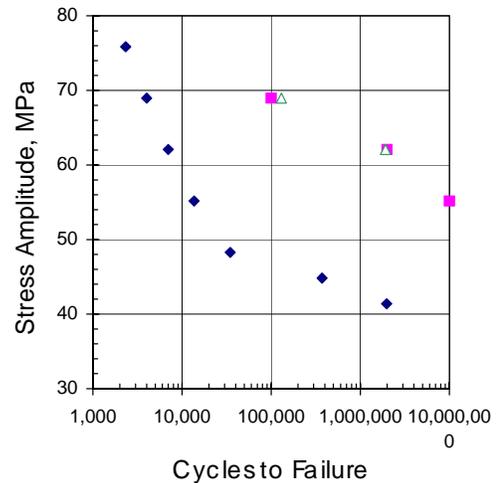


Figure 4. Advantages of HMG based plastics for the design of cyclically stressed components. Legend: \square - HMG plastics; 63 wt.% GF, \square - 33 wt.% GF.; Materials state - DAM at tests start, color - natural state.

Key Words

Nylon, strength, fatigue life, creep, weldability.

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