ABSTRACT

Due to the wide and ever increasing application of thermoplastics for the transportation and automotive industries, the performance of under-the-hood plastic parts depend, upon optimized design and processing technology and properties of polymer based materials. Nylon (polyamide) based plastics are used widely for automotive cooling fans and various under-the-hood injection molded components.

For injection molding of multi-blade cooling fans and various rotating plastic parts the complex of multiple gating injection molding tools were used. Both the design of the various rotating parts (including industrial and automotive cooling fan, and the molding tool design are very important to get optimum flow patterns and to predict the locations and interaction of stress-bearing areas and knit lines (planes or inter-phases). The mechanical performance of the injection-molded thermoplastic components depends on the peculiarity of the part and the molding tool design.

In Part 1 of this paper, we are presenting results of structural design analysis (comprehensive analytical and linear FEA) and design optimization of a multiple gated rotating components with a ring under the influence of the design parameters. In Part 2 of this paper, we are discussing the mechanical properties of fiber-glass reinforced thermoplastic in local (weld plane) and bulk (molded part) areas with the influence of molding and end-use conditions.

The analysis of this study shows, that for non-reinforced or non-filled nylon, the mechanical performance in the knit-line (weld plane) areas are approximately equal to the mechanical performance of used resin (polyamide).

INTRODUCTION

There are many design and technology cases, which require multiple gates injection molding systems. Mechanical performance of these injection molded multiple gated plastic parts, depends from uniform distribution and orientation of flow and the material property patterns. For automotive cooling fans, the main requirements are for airflow and mechanical performance (short-term strength, including impact, creep and fatigue life). Fan shrouds’ main requirements are additionally for rigidity and dimensional stability, often in quite thin sections, rather than impact strength and creep. High performance fiber-glass reinforced and glass/mineral versions of nylon 6 were utilized in many applications [4-7].

There are many round/circular thermoplastic parts and components similar by configuration and processing technology to the cooling fans with a ring, such as wheels (for arm-chairs and sports bikes, etc.), housings, rotating discs with the bores, impellers, etc. The similar principles of the part and mold design and molded part mechanical performance analysis may be applied for these groups of thermoplastic made components.

NATURE AND STRUCTURAL INTEGRITY OF KNIT (WELD) LINES

For fiber-glass reinforced and fiber-glass/mineral nylon, the mechanical properties of plastic in the knit (weld) line (plane) are different from the basic mechanical properties of reinforced plastic due to flow patterns and local fiber-glass re-orientation in the weld plane areas. Due to the above changes, the knit (weld) lines become likely areas of crack initiation and propagation and possible molded part failure or damage.

The results from this complex study should help plastic part designers to accurately interpret the results of the structural analysis and complex tensile properties such as strength, deformation and fatigue of nylon based plastics and to utilize these important material parameters at end-use conditions for a plastic part life assessment.
In Part 1 of this paper, we discussed the principles of knit and meld lines formations. If the melt is flowing around of any obstacles in the mold tool, such as the inserts, ribs, cores, etc., a weld or meld line will result. The weld and meld lines (planes) are created wherever polymer flow’s front meet from opposite or parallel directions correspondingly (Figure 1).

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

Weld lines are weaker than meld lines [1, 5]. Due to the above described changes, these weld planes (lines) become likely areas of the crack initiation and propagation and possible molded part failure. These weaknesses can change the thermoplastic strength and deformation parameters.

A family of knit (weld) lines may be formed from one gate, and the divided plastic streams joins after flowing through spokes (or blades) and a ring (Figures 2 and 3). Knit (weld) line will be formed between every pair of the spokes (or blades). For the multi-blades cooling fan with a ring, the knit (weld) lines will be created between every two opposite melt flows in a ring area (see: Part 1, Figure 7 and Figures 15-16).

As a rule, the location of these knit (weld) lines is between every pair of the spokes (or blades). In a ring with a complex shape (containing interior and outer layers), the knit lines will be formed first in the interior layer (Figure 2a) and later in the outer layer (Figure 2b).

3 In the mechanical performance and morphology analysis we will use also the term “inter-phase” also, as the three dimensional description of this very complicated by glass-fibers and polymer chains re-orientation areas.
Knit (weld) line is in the direction perpendicular to applied stress. For fiber-glass reinforced thermoplastics, the strength in these local areas (knit/weld and meld lines) is less than in bulk areas, due to the orientation effects (Figure 7b).

The extent of physical and mechanical property change depends on the ability of the two melt flows to knit (joint) together homogeneously through molded part thickness and a length of knit line(s). Orientation of these knit (weld) lines is perpendicular to the tensile stresses, applied to the ring (Figure 2-4). The maximum of tensile strength of molded plastic is in the direction parallel to flow (Figure 7a).

In order to achieve controlled fill patterns, the mold designer should select the location and number of gates that will result in the desired areas. Molding parameters are influential on melt flow formation and finally on the performance of the knit (weld) line (inter-phase).

For fiber-glass reinforced thermoplastic the knit (weld) planes, formed by the re-joining or cooling of two melt flows, are typically weaker than non-knit (weld) areas due the following reasons:

- There is a sharp notch at the knit/weld plane (inter-phase) that acts as the stress/strain concentrator
- Fiber-glass orientation in the knit/weld inter-phase occurs at the right angles to the principal melt flow patterns
- This orientation is contributed to the strength reduction in the weld inter-phase area.
The example of melt flow temperature distribution at the end of the fill cycle is presented in Figure 6 and Table 1.

![Figure 6](image1)

**Figure 6.** Molding analysis study: An example of the melt flow temperature distribution through ISO tensile specimen gated from both sides thickness (MoldFlow® data, nylon 6, 33 wt.% GF). Legend: a – skin layer/area; b – inter-layer (between the skin and a melt core); c – flow/melt core central layer.

These results are showing the possibility for different cooling conditions for the skin and core layers. This will affect crystallinity distribution through cross-section of molded part/specimen also.

A practical thermoplastic part design – melt flow consideration is to combine concepts of full optimization of mechanical performance of thermoplastic parts where multiple gating systems were used. The number of gates and internal shutoff cores should be considered as an important aspect of:

- Initial thermoplastic part design
- Prediction of part performance with the influence of location of stress-bearing areas and weld planes/lines.

**Table 1.** Melt Temperature (°C) Distribution Through Thickness of Doubled Gated ISO Tensile Specimen at the End of Packaging Cycle

<table>
<thead>
<tr>
<th>Position of the melt layer through thickness</th>
<th>Gate</th>
<th>Knit-Line (Plane)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin area (a)</td>
<td>77.4</td>
<td>67.4</td>
</tr>
<tr>
<td>Inter-layer (b)</td>
<td>158.5</td>
<td>277.8</td>
</tr>
<tr>
<td>Central core (c)</td>
<td>280.2</td>
<td>281.6</td>
</tr>
</tbody>
</table>

![Figure 7](image2)

**Figure 7.** The effect of melt flow orientation on mechanical performance of injection molded parts/specimens. Legend: a – applied stress is parallel to flow direction (unidirectional fiber-glass orientation); b – applied stress is perpendicular to the knit (weld) line.

Standard mold filling and cooling analysis (MoldFlow® data, Figures 2-3 and 6) provide the designer and technologist with a quantitative data on flow patterns and the knit/weld lines (planes). Critical plastic flow distance, and the number of gates and internal shutoff cores should be considered an important factor of thermoplastic part design for required uniform mechanical/physical performance [1, 5].

Unfortunately, it was not possible to find in the published literature detailed recommendations on thermoplastic selection and design for multi-gated round/circular parts with a ring. Published data on mechanical performance of nylon in knit (weld) line is limited also [2, 5, 8].

Previously it was assumed [9] to use for design purposes the tensile strength of knit (weld) line in range...
from 50 to 95% of base material\(^4\) strength. This range of the ultimate strength is very wide for design purposes and needs to be defined more precisely for the critically loaded components containing various knit/weld lines.

These recommendations and specific data on localized material properties in knit/weld area is very important for the structural analysis and life assessment of injection molded (using multiple gating system) automotive cooling fans with a ring.

**NYLON BASED PLASTICS – MATERIAL OF CHOICE FOR AUTOMOTIVE UNDER-THE-HOOD COMPONENTS**

Plastics offer the automotive under-the-hood manufacturers the following key benefits – weight saving, improved performance and style. Integration of function is a much benefit of plastics molding, turning the assembly of multiple metal cooling fans from the past into today’s [10]. There are different types of injection-molded nylons [2, 4-7, 11] providing wide range of end-use performance for many automotive applications (under-the-hood, body, interior, exterior, etc.).

Under-the-hood nylon 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. Nylons (polyamides) are high performance semi-crystalline thermoplastics with a number of attractive physical and mechanical properties. Injection molded nylon components including cooling fans and shrouds are used in many industrial applications, the largest being automotive. There are more than a dozen classes of polyamide (PA)/nylon resins, including nylon 6, nylon 66, nylon 46, nylon 10, nylon 12, etc.

Three important thermoplastic – molding tool – plastic part interrelations must be considered at the outset by those specifying polyamide (nylon): nylon 6 is a family of related plastics, not a just a single composition [1, 12].

Reinforced nylon plastics (with 15 – 40 wt.% fiber-glass reinforcements - GF\(^5\)) are commonly used in design of automotive cooling fans and shrouds [4, 6-7]. Fiber-glass reinforced and mineral filled nylon plastics (25 – 45 wt.% GF/MF) are used in design of shrouds also [10]. Typically, the weight of glass-fiber reinforced nylon-based automotive part is 40-55% less than a similar design made from stamped steel [4, 7]. The similar weight reduction was achieved for automotive cooling fans also [4, 13].

This family of fiber-glass reinforced or reinforced and filled plastics [2, 4-6] can be considered, that all compositions have the following injection molding advantages [1, 12] for automotive cooling fans:

- Good mechanical performance of molded part/specimen 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) is 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 the fan blades
- Sufficient knit (weld) line strength.

**THE KEY MECHANICAL PROPERTIES NEEDED FOR DESIGN OF PLASTIC COOLING FANS**

Thermoplastic selection for automotive cooling system processing must be based on both end-use requirements (including mechanical and airflow performance) and molding processing conditions [10, 12]. For mechanical performance prediction of automotive cooling fans, we need to use the various physical and mechanical properties of injection-molded nylons.

Key mechanical properties needed for design of plastic cooling fans should be developed with the influence of a cooling fan and molding tool design and processing technology features. Mechanical test results need to be conducted at various end-use environmental and mechanical loading conditions, typical for under-the-hood applications.

The following base/key mechanical properties of materials are very important for designing with plastics:

- Short-term properties
- Long-term properties.

Short-term mechanical performance of thermoplastics is important for quality control to ensure the constant properties of raw materials and injection molded parts. The following long-term properties of engineering thermoplastics are more important in predicting of the

\(^4\) The definition of the strength of base material is not clear enough in used trade literature and published reports. By our opinion “the strength of base material” is strength of the matrix, but not strength of reinforced plastic.

\(^5\) wt.% - level of reinforcement or filled by weight.
service time of under-the-hood components: creep, fatigue and repeatable impact.

**Short-Term Tensile Properties**

Comprehensive tensile properties of non-reinforced and fiber-glass reinforced plastic should include the following key strength and deformation parameters needed for an analytical and FEA (Young modulus, Poisson’s ratio, tensile strength at break, ultimate elongation at break).

Short-term tensile properties for three grades of nylon 6 based plastics are shown [11] in Table 2.

Table 2. Properties of Capron® Nylon 6 Based Plastics (all HS – Heat Resistance Package) at Room Temperature (23°C, Dry-as Molded, DAM)

<table>
<thead>
<tr>
<th>Mechanical Properties and Capron Version (all HS)</th>
<th>8202</th>
<th>8231G</th>
<th>8233G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber-glass content, wt.%</td>
<td>0</td>
<td>15</td>
<td>33</td>
</tr>
<tr>
<td>Density, gm/ cm³</td>
<td>1.13</td>
<td>1.26</td>
<td>1.40</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>Tensile Strength, Mpa</td>
<td>85</td>
<td>134</td>
<td>192</td>
</tr>
<tr>
<td>Young Modulus (x10³), MPa</td>
<td>3.43</td>
<td>5.96</td>
<td>9.88</td>
</tr>
<tr>
<td>Ultimate Elongation, %</td>
<td>70</td>
<td>3.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Flexural Strength, Mpa</td>
<td>112</td>
<td>180</td>
<td>270</td>
</tr>
<tr>
<td>Notched Izod Impact, J/m</td>
<td>55</td>
<td>60</td>
<td>115</td>
</tr>
</tbody>
</table>

The influence of such factors as time, temperature, moisture, plastic composition (additives, fillers and reinforcements), molecular orientation, and crystallinity distribution are very important for the performance of injection molded parts.

Because all nyons are moisture sensitive thermoplastics (Table 3), this short-term data should present mechanical performance of the standard specimens and molded parts at various level of moisture in typical for manufacturing and end-use.

Table 3. Influence of Relative Humidity on Water Absorption (in %) in Non-Filled Nylons (at 23°C in air) [5]

<table>
<thead>
<tr>
<th>Type of PA</th>
<th>30% RH</th>
<th>50% RH</th>
<th>62% RH</th>
<th>100% RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA6</td>
<td>1.1</td>
<td>2.75</td>
<td>3.85</td>
<td>9.5</td>
</tr>
<tr>
<td>PA66</td>
<td>1.0</td>
<td>2.5</td>
<td>3.6</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Under room temperature and 50% RH nylon 6 could eventually absorb 2.75-2.8 wt.% water. Every one wt.% moisture increase in nylon may result in 0.2 to 0.3% increase in dimension.

The relation between absorbed moisture in injection molded parts or specimens and time of exposure is different for different thickness of nylon made parts (Figure 8).

Figure 8. Moisture absorption vs. time for 33% glass fiber reinforced nylon 6 molded in plaques with various thickness (mm): 3.2; 4.0; 6.25.

Under dry-as-molded conditions (DAM) nylon usually contain 0.1-0.3 wt.% water⁷. By controlling moisture

⁶ Capron® - is a registered trademark for BASF Corporation nylon based plastic products

⁷ ASTM D-4066 specified for nylon 6 moisture content “as received”, before the package is opened and the material exposed to the outside air, equal 0.2 wt.%.
content in that range, it is possible to reduce brittle failure of the molded parts. After a bag or container with the pellets has been open and plastic exposed to the air, the nylon pellets starts picking up moisture.

An initially dry (0.1-0.3 wt.% ) nylon at room temperature conditions (23°C) and 50% RH will raise the moisture level by 0.3 wt.% in 4 hours and 0.45 wt. % in 8 hours.

For winter conditions (when it is cold and dry, 25% RH), the time required to pick up 0.45 wt.% moisture would be about 50 hours.

As rule, ISO 1110 procedures (62±1 %RH at 70°C) were utilized in this study for conditioning of the molded various under-the-hood components and test specimens.

Figure 9 show changes in tensile strength at wide range of moisture and temperature effects. At –40°C tensile strength was change very slightly (decreases by 10% approximately).

The significant changes were observed at room temperature (23°C): the tensile strength decreases by 45%. At elevated temperature (from 80 to 150°C), tensile strength decrease by 20% approximately.

![Tensile Strength vs. Moisture Content at Different Temperatures](image)

**Figure 9.** Influence of temperature and moisture on the tensile strength of reinforced nylon 6 (33% glass-fiber).

In nylons, absorbed water exist in the amorphous phase, yet its presence could influence both crystallization and crystalline phases. With water absorption, γ phase is transformed to the more stable α phase.

Absorbed water behaves as a plasticizer that decreases glass transition temperature ($T_g$) which lowers tensile strength and Young’s Modulus (E). Moisture and temperature have similar effects on the tensile properties of nylon.

Effects of moisture on tensile strength and Young’s modulus is shown in Figures 9 and 10. Changes in moisture content (from 0.2% to 1.2%) affect the decrease of the tensile strength and Young’s modulus and increase of tensile strain at tensile strength (Figure 11).

Changes in moisture content (from 0.2% to 1.2%) affect the decrease of the tensile strength and Young modulus and increase of tensile strain at tensile strength (Figure 11).

Moisture content increase from 1.2% to 1.75% is not so significantly affected to tensile properties of fiber-glass reinforced nylon 6 in comprizing with the range 0.2 – 1.2% (Figure 10 and 11).

At this range of moisture content changes, the reduction of the tensile strength (for 33 wt.% GF) is 5-6% approximately. Tensile strains will increas by 15-20%.
The blades of flexible cooling fans are under combined axial and flexural loading conditions (Figure 12). The range of speed for all rotating under-the-hood parts range from 2,000 rpm to 9,000 rpm. At this loading condition it is very important to take into account the influence of inertial axial load and flexural effects initiated from airflow pressure. Resistance to creep is critical to areas of assembly where long-term stress-relaxation processes are typical.

*Specifics of the Loading and Conditions for the Fans with the Flexible Blades (without a Ring)*

The normal centrifugal force at the cross section $y$ is

$$p(y) = \int_y^{R_0} y^2 \omega^2 \, dm = \int_y^{R_0} t_b b \rho \omega^2 y' \, dy$$

$$= t_b b \rho \omega^2 (R_0^2 - y^2)/2$$

Then normal stress in cross-section $y$ is equal

$$\sigma(y) = \rho \omega^2 (R_0^2 - y^2)/2$$

The maximum stress is at intersection of a blade with a hub, when $y = 0$.

$$\sigma(\text{max}) = \rho \omega^2 (R_0^2)/2$$

---

**Figure 10.** Influence of temperature and moisture on Young’s modulus of fiber-glass reinforced nylon 6 (33% glass-fiber).

Analyzed combined temperature and moisture effects are very important for cooling fan design on the stage of material pre-selection and initial FEA (by short-term strength criterion). Prediction of the long-term cyclic performance of the automotive cooling fans require having comprehensive long-term (fatigue) properties of used thermoplastics.

**Figure 11.** Effect of moisture on tensile properties of fiber-glass reinforced nylon 6 (33 wt.%): Tensile strength and strain at yield vs. moisture at room temperature (23°C).

**Long-Term Properties: Fatigue and Influence of Aging**
For start-stop conditions of a cooling cycle it will represent “pulsing cycle” and stress amplitude is equal

\[ \sigma(a) = \rho \omega^2 \left( R_0^2 \right) / 4 \]  \hspace{1cm} (5)

Loading conditions of a separate flexible blade and airflow path for automotive cooling fan with a ring is shown in Figure 13.

**Specifics of the Loading Conditions for the Fan with a Ring**

Maximum normal stress at a ring area is equal

\[ \sigma_{MAX} = \sigma_{R1} + \sigma_{R2} \]  \hspace{1cm} (6)

where:

- \( \sigma_{R1} \) - maximum normal stress in a ring
- \( \sigma_{R2} \) - maximum bending stress at mid-point of a ring (knit-plane area).

Cyclic stress amplitude \( \sigma_a \) can be defined as

\[ \sigma_a = \sigma_{max} / 2 \]  \hspace{1cm} (9)

The fatigue strength (endurance limit) of most thermoplastics is about 20 to 30 percent of the ultimate tensile strength determined in the short-term test conditions (Figure 14).

Figure 14. Influence of moisture effects on flexural fatigue performance of nylon 6 based plastic (33 wt.% GF) at room temperature conditions (23°C).

Figure 15. Resistance to tensile-tensile fatigue of nylon 6 based plastic (33 wt.% GF) with the influence of temperatures effects

Higher fatigue strength is for reinforced plastics. It decreases with increases in temperature (Figure 15) and stress-strain cycle frequency. Moisture and temperature reduces resistance to fatigue of nylon based plastics (Figures 14 and 15).

Flexural fatigue data (Figure 14) is very important for the design of the fans with flexible blades. Resistance to tensile-tensile fatigue is critical for the fans with a ring containing the knit/weld lines. Higher fatigue performance is achieved when the S – N data are for tensile loading conditions with the stress ratio equal 0.
The number of the start-stop cycles is the key factor in design of the fans with a ring.

Long-term temperature effects (up to 1,500 hours) will not effect the degradation of mechanical properties of nylon-based plastics (Figure 16) and maximum reduction (up to 25%) was achieved at 2,000 hours and 135°C.

**Thermal Degradation**

![Graph showing thermal degradation](image)

Figure 16. Influence of the long-term aging on mechanical performance on nylon 6 (33 wt.% GF).

**WELD AND MELD PLANE (LINE) INTEGRITY**

**Weld Line (Plane) Strength**

Overall thermoplastic part design should be scrutinized for redundancy and simplified to require the least less complicated injection mold design. In the design of complicated shapes, weld planes/lines and meld lines are often unavoidable.

Information on the effects of injection molding variables on mechanical performance of nyons is not abundant, and a part of these results are discrepant. But what does exist for non-nyons gives us the following guidelines [1, 9]:

- Increasing both melt and mold temperatures will increase weld line tensile strength
- Excessive melt temperatures will degrade the joined polymer causing a general strength reduction of the bulk, including weakness at the weld plane
- Fill rate and packing pressure effects are positive in limited areas only.

Higher melt temperature promotes polymer molecular knitting and chains entanglement at the weld inter-phase and yield less net orientation. Increasing mold temperature promotes slow cooling. In most cases the mold temperature effects (they are positive) is not so effective as the melt temperature effects.

Effects of these complex changes can also depend on particular grade of thermoplastic, molded part design, and mold and melt temperature levels.

The effects of the inherent weld plane integrity were analyzed in [11-13]. In this study were evaluated the effects of the weld plane on tensile strength of four plastics (polysulfone – PSU, styrene acrylonitrile – SAN, polypropylene – PP, and polyphenylene sulfide – PPS).

It was found that the percentage of loss in strength at the weld line is greatly increased by fiber reinforcement. However, absolute weld line strength increases as more or stronger reinforcement is added. The large loss of strength at weld line fiber-glass reinforcement is caused by improper fiber orientation.

Mechanical performance of various nylon 6 plastics at knit-line/plane area is shown in Table 5.

When the tensile strength of the thermoplastic increases from 86.5 to 192 MPa (at the range of glass-reinforcement from 0 to 33 wt.% GF), tensile strength retention for the knit-line/plane decreases from 99 to 46% (see Table 5).

But at the same time, the tensile strength at the knit-line/plane remains the same for all levels of fiber-glass reinforcement and is equal (approximately) or slightly above of the tensile strength of non-reinforced plastic (86.5 ÷ 89.2 MPa).

<table>
<thead>
<tr>
<th>Type of Resin</th>
<th>Glass-Fiber Content, wt. %</th>
<th>Tensile Strength of Plastic, MPa</th>
<th>Tensile Strength at Weld Plane, MPa</th>
<th>Tensile Strength Retention, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSU</td>
<td>0</td>
<td>65.0</td>
<td>65.0</td>
<td>100</td>
</tr>
<tr>
<td>PSU</td>
<td>30</td>
<td>115</td>
<td>70</td>
<td>62</td>
</tr>
<tr>
<td>SAN</td>
<td>0</td>
<td>80</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>SAN</td>
<td>30</td>
<td>110</td>
<td>45</td>
<td>40</td>
</tr>
<tr>
<td>PP</td>
<td>0</td>
<td>35</td>
<td>35</td>
<td>100</td>
</tr>
<tr>
<td>PP</td>
<td>20</td>
<td>65</td>
<td>30</td>
<td>47</td>
</tr>
<tr>
<td>PPS</td>
<td>0</td>
<td>60</td>
<td>50</td>
<td>83</td>
</tr>
<tr>
<td>PPS</td>
<td>10</td>
<td>70</td>
<td>25</td>
<td>38</td>
</tr>
</tbody>
</table>
Table 5. Effects of Reinforcement on Weld Line Integrity of fiber-glass reinforced nylon 6 based plastics (Capron® series).

<table>
<thead>
<tr>
<th>Type of Resin</th>
<th>Glass-Fiber Content, wt. %</th>
<th>Tensile Strength of Plastic, MPa</th>
<th>Tensile Strength at Weld Plane, MPa</th>
<th>Tensile Strength Retention, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA6</td>
<td>0</td>
<td>86.5</td>
<td>85.8</td>
<td>99.2</td>
</tr>
<tr>
<td>PA6</td>
<td>15</td>
<td>133.8</td>
<td>89.1</td>
<td>66.6</td>
</tr>
<tr>
<td>PA6</td>
<td>15%GF + 25%MF</td>
<td>125.7</td>
<td>84.0</td>
<td>66.8</td>
</tr>
<tr>
<td>PA6</td>
<td>33</td>
<td>192.9</td>
<td>89.2</td>
<td>46.2</td>
</tr>
</tbody>
</table>

Similar results were obtained for nylon 66 based plastic (Table 6) with the same level of fiber-glass reinforcement.

Table 6. Weld Line Integrity of nylon 6 and nylon 66 based plastics (33 wt.% GF, Capron® series)

<table>
<thead>
<tr>
<th>Type of Resin</th>
<th>Glass-Fiber Content, wt. %</th>
<th>Tensile Strength of Plastic, MPa</th>
<th>Tensile Strength at Weld Plane, MPa</th>
<th>Tensile Strength Retention, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA6</td>
<td>33</td>
<td>192.9</td>
<td>89.2</td>
<td>46.2</td>
</tr>
<tr>
<td>PA66</td>
<td>33</td>
<td>190.8</td>
<td>88.5</td>
<td>46.3</td>
</tr>
</tbody>
</table>

Melt-Flow Orientation and Morphology of the Knit-Lines/Planes

Mechanical performance of the injection molded or extruded parts, strongly depends on processing technology and part design. To illustrate the influence of injection molding processing technology on fiber-glass glass orientation and mechanical performance of plastic components, the multipurpose test specimen (ISO 3167) was analyzed (Figures 17, 18 and 19) and related to what may happen in injection molded automotive under-the-hood part.

For this investigation we used two sets of similar specimens molded from 33 wt.% GF nylon 6:

- One side/end gated (Figure 17 and 18)
- Doubled (two side) gated (Figure 19).

Tensile test data for both sets of ISO multipurpose specimens is presented in Tables 5 and 6.

Figure 17. Example of orthotropic (unidirectional) fiber glass orientation in molded part/specimen (one side gated). Data obtained using injection molded nylon 6, 33 wt.% GF multipurpose specimen (ISO 3167) at flow direction.

Fiber-glass reinforcements display flow orientation during injection molding. The degree of orientation
(fiber-glass and molecular) depends on aspect ratio, plastic part dimensions, injection rate, and gating. A one side/end gated ISO multipurpose specimen will have fiber-glass orientation mostly oriented along the length axis (Figure 17). Such plastic flow orientation leads to clearly defined anisotropy of mechanical properties in fiber-glass reinforced nylon.

Figure 18. Example of random fiber-glass orientation in molded part/specimen (one side gated). Data obtained from injection molded nylon 6, 33 wt.% GF multipurpose specimen (ISO 3167) close to gate area

At the gate area, fiber-glass orientations are random for both sets of the injection molded specimens (one and both sides gated). The tensile strength and modulus reaches a maximum value in the flow (longitudinal) directions (Figure 17) and up to 50% less in the transverse (perpendicular to flow) direction. For 33 wt.% GF nylon 6 this decrease might reach up to 50 – 60% of the similar value due to micro-cracks orientation.

Figure 19. Example of fiber-glass orientation at knit (weld) inter-phase area in molded part/specimen (doubled/two sides gated). Data obtained using injection molded nylon 6, 33 wt.% GF multipurpose specimen (ISO 3167).

Figure 20. Example of fiber-glass orientation at knit-line (weld inter-phase area) in injection molded multi-gated part. Data obtained using nylon 6, 33 wt.% GF.

Double-gated multipurpose specimens develop knit-lines/planes that are critical for the loading/maximum stress area that results in the mechanical performance of the specimens.

As melt flow fronts meet, the fibers are turned 90° from the direction of flow. This is 90° from the direction of expected applied tensile stresses, so fibers are aligned perpendicular to the applied tensile stress and offer little reinforcing effects at weld plane. Molded part/specimen thickness does not play a major role in weld line strength retention.

The observed increase in the tensile strength at the knit-line/plane for 33 wt.% GF nylon 6 from 86.5 MPa (tensile strength of matrix/resin) to 89.2 MPa (knit-line) can be explained by the following:

- As a result of a local reinforcement in the knit-line (inter-phase, Figure 19)
- Diffusion of the joined layers/flows
- As the result of optimized molding conditions.

Conventional techniques to optimize knit-line/plane strength are:

- Increase melt temperature;
• Increase mold temperature;
• Increase injection pressure; and
• Avoid use of external release mold lubricant (mold release).

Some Recommendations and Suggestions for the Part Design, Processing Technology and Material Selection

The surface that is to be subject to high load-bearing should not contain weld planes/lines. If it is not possible, the allowable working stress should be reduced by at least 15% [3, 8].

For impact modified plastics at the high molding temperature, the additive concentrate, at the part surface and the weld inter-face, because of a phenomenon called “fountain flow”. For this phenomenon, the melt does not reach the wall or surface of the frozen wall layer by simple forward advance, but rather tends to flow down to center of the cavity to the melt front and then flow toward the wall.

This can have an important effect on the direction of the flow-induced orientation of the polymer molecules. If the melt flows around an obstacle of any kind in the cavity, a weld line will result.

For the multiple gating system, the flow is largely governed by the dimension and shape of the article and the location and sizes of the gates.

A phenomenon that can lead to the complex patterns of weld lines is “jetting”. A good flow will insure uniform mold filling and prevent the formation of layers.

Jetting can be prevented by enlarging a gate size or gate orientation in such way, that the flow is directed against a cavity wall. In a case of big enlarging gate size, the flow slow down and weld lines may also be formed at the place where a wall thickness increase suddenly.

CONCLUDING REMARKS

• Weld planes (lines) become likely areas of a crack initiation and propagation, and possible molded part(s) failure (or damage).
• For non-reinforced (or non-filled) nylon the mechanical performance in weld plane areas are approximately equal to mechanical performance of used resin (matrix).
• Fiber-glass reinforced and fiber-glass/mineral nyons have the mechanical properties of plastic in knit (weld) line (plane), which are different from basic mechanical properties of reinforced plastic due to flow patterns and local fiber-glass re-orientation in weld plane areas.
• Un-reinforced and short glass-fiber reinforced (15 to 35 wt.% GF) nylon based plastics are materials of choice for an automotive cooling fans.
• Un-reinforced or moderate reinforced (up 20 wt.% GF) nylon in design of the fans with the flexible blades for non harsh elevated temperature conditions.
• Glass-fiber reinforced nylon based plastics shall be recommended for the design of the cooling fans with the flexible blades for high temperature conditions and for the cooling fans with a ring.
• Ultimate state of cyclically loaded cooling fans are as follows:
  ♦ Resistance of a blade to the fatigue in areas close to the hub (for molded fans with the flexible blades); and
  ♦ Resistance of a ring to the fatigue in knit (weld) line area (for multiple gating injection molded fans with a ring).
• Moisture and temperature have similar effects on the mechanical performance of injection molded nylon fans and specimens. With moisture (or temperature), growth (increase of temperature) mechanical performance decreases (except impact strength).
• The effect of moisture content on mechanical performance of injection molded nylon fans is more pronounced at room temperature conditions and it less significant at lower (-40°C) and at elevated temperatures (up to 150°C).

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REFERENCES


KEYWORDS
Nylon; polyamide; plastic; thermoplastic; knit line; weld line; weld plane; weld inter-phase; stress; strain; tensile; flexural; moisture; temperature; relative humidity; conditioning; fiber-glass; reinforcement; automotive; cooling fan; blade; ring.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

**ASTM**: American Society of Testing and Materials

**BK**: carbon black

**GF**: fiber-glass reinforcement

**ISO**: International Organization for Standardization

**MF**: mineral filled

**PA**: polyamide

**PP**: polypropylene

**PPS**: polyphenylene sulfide

**PSU**: polysulfone

**RH**: relative humidity

**SAE**: The Engineering Society for Advancing Mobility

**Land Sea Air and Space**

**SPE**: Society of Plastic Engineers

**SAN**: styrene acrylonitrile

**E** – Young’s modulus of the fan material/plastic

Term:
**Conditioning**: the whole series of operations intended to bring a plastic part/sample into a state of equilibrium with regard to temperature and humidity.

**Melt line**: the mark visible on the finished molded part/specimens, where two plastic flow fronts from different but not opposite direction met during molding.

**Moisture equilibrium**: the conditions reached by a plastic part/specimen when it no longer takes up moisture from, or gives up moisture to, surrounded environment.

**Test atmosphere**: the atmosphere to which a plastic part/sample is exposed through the test.

**Weld line**: the mark visible on a finished molded part/specimen made by the meeting of two flow fronts of thermoplastic material during molding. Also called weld mark, flow line or knit line.

**Weld plane**: the area or plane in which two polymer/plastic flow fronts meet as the cavity is filled is commonly called a weld plane or weld line commonly called a weld plane or weld line (see above please).
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