

DESIGN OF PLASTIC RIM FOR INDUSTRIAL AND COMMERCIAL
LIGHT VEHICLES USING MODELING AND SIMULATION TOOLS

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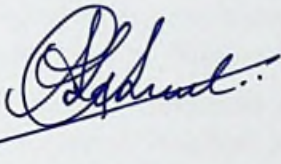
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Abstract

The present research was devoted to designing a plastic rim for industrial and commercial light vehicles using modeling and simulation tools.

The main objective of the design project was to design a rim structure that would be capable of sustaining the required load and performing under provided service conditions. In order to select a suitable thermoplastic composite a series of plastics was experimented. The selection of material was based on several factors, including mechanical strength under dynamic load, resistance to prolonged action of elevated temperatures and ability to be molded with conventional techniques. The materials which were considered for the design included Polyamide 6, Polyamide 6 with 50% long glass fibers, Polyamide 6 with 50% short glass fibers and Polyamide 6 with 30% short glass fibers, out of which Polyamide 6 with 30% short glass fibers was selected due to it being less brittle, that aided the material to withstand service and accidental impact. Another criterion that supported selected material was associated with its ability to be injection molded with conventional type injection molding techniques.

Four models were developed based on general plastic product design standards. Each model was simulated in order to identify areas of potential failure. After that model was optimized by changing its structural arrangements so as the stresses in the potential failure areas were reduced. Next step in modification and optimization of the model was done for product mold-ability.

The model which comprised a solid body of rim portion with a center bore configured to receive axle hub, an inner band, a circumferentially extended outer band that margined the rim portion, a nave ring that extended outwardly and radially of said center bore wherein a plurality of holes were circularly positioned that were configured to receive bolts, a plurality of ribs extending outwardly and radially at right angles from the nave ring up to the outer band were positioned both sides of the rim configured to improve flexural rigidity of the structure was accepted for fabrication by means of reinforcement of hub hole area with metal plate.

A manufacturing method of plastic rim was selected based on the material processibility, manufacturing cost and efficiency for serial manufacturing and commercialization. Prototype Injection mold was manufactured using cheap and easy to machined steel P-20. Produced standard mold was modified to improve ventilation and to facilitate flow of the plastic melt through the flow path of the injection mold from machine nozzle to cavity

The successful prototypes and destructive tests carried out affirmed suitability of the Solidwork Design package and Solidwork Simulation Package for designing, manufacturing and prediction of load bearing capability of the plastic rim. The application of Solidwork Simulation Package during designing stage lead to reduced implementation cost and reduced reproduction numbers of prototypes to evaluate product suitability, thereby making implementation of the final product efficient.

The main advantages of using plastic composite material for automotive rims included energy efficiency and easy maintenance due to lower weight

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1. Introduction

1.1. Background

The vehicle innovations are attempting to make vehicle to run more mileage out of a volume of fuel with the minimum emissions to the environment. It is well known, that the emitted carbon-based gases from vehicles heat the atmosphere causing damaging climate changes, producing pollutants and reducing overall air quality and effecting adversely on public health especially in heavily-populated urban areas.

Innovative materials and technologies open up new approaches to the solution of the above problem such as introduction of plug in electric vehicles with almost zero emissions (1).

Another approach is designing of multifunctional light weight constructions evident by matter of physics, the lighter the vehicle, the less power it requires to get moving and the less energy needed to maintain a constant speed. Therefore reduction in weight of vehicle directly impacts reduction of fuel consumption. Such light weighted cars can play a key role in reducing carbon dioxide emissions as well. Reducing weight by five percent in the small car with a 1.6-liter engine, led to an increase in fuel economy by 2.1 percent. Eliminating 10 percent of the weight gave a 4.1 percent mileage boost and a dramatic 20 percent weight decrease improved fuel economy by 8.4 percent (2).

Intelligent light weighted construction can be designed using light weighted materials like glass fiber composites, thermoplastics, thermo-sets and aluminum or carbon fibers instead of steel. The benefits of application of those materials are well known. Advanced plastics and composites not only reduce cars' weight but also provide car designers with a freedom of expression that would not be possible with conventional metals, like steel and aluminum. Due to this reason, usage of plastics in automobile industry has been increasing rapidly during last few years and it is expected by 2020 an average car will incorporate nearly 350 kg of plastics compared to 200 kg in 2014 (3).

From a practical perspective, automakers are adopting new materials in order to reduce the weight of vehicles to comply with government regulations setting certain mileage per gallon of used fuel. In order to meet for example U.S. and European standards for greenhouse gas emissions for 2020 and 2025, car road loads must be

reduced by 30 percent (3). This will be possible to achieve by focusing mainly on further reduction of weight of engine, transmission and most easily on body work hence the tires and rims are expected to play a major role. In this contest the attention of many design engineers is now brought to design of a plastic rim that will be able to replace steel rim. Application of plastic composite wheels on highest trim level vehicles surely carries its advantages equivalent to the price being quoted.

European primer brands of motor car manufacturer enjoy shaper steering, better handling and riding comfort, better acceleration, reduction of noise and vibration reduction of road harshness and benefit fuel economy due to eliminating approximately 38.8 pounds (18 kg) of weight per vehicle with only one plastic rim used instead of steel one. The plastic rims remain still privilege restricted to high end sports cars and very expensive E-drive cars as their high price related mainly to cost of materials, design, and crash analysis and manufacturing processes. Despite of this, there are some cost effective solutions leading to applications of plastic and composite wheels in day to day non highway indoor and outdoor vehicles (4). Some of the few examples are Trolleys and Dolly's, small forklifts, lawn movers and casters. The wheels for those vehicles are made of composites materials based on general use plastics and engineering plastics which are of low cost and capable to perform well under certain conditions in where low speed and moderate load applied.

As finite element method (FEM) analysis using 3D modeling and simulation make it possible to design and optimize structure for safe performance at affordable cost, the design of plastic rim for commonly used vehicles becomes an achievable task.

Several studies (5) have been carried out in these directions. It was shown that plastic rim behaved in a manner different than similar structural components made of conventional materials like steel and aluminum. The plastic rim failure occurs in micro modes, such as matrix cracking, delimitation even fiber breakage

The complex fracture mechanisms makes it difficult to understand and to predict analytically behavior of plastic rim in dynamics and requires further study to ensure strength and stability of the plastic structure for safety and benefits of environmentally sustainable and fuel efficient vehicles. In this context the present project was carried out to design plastic rim for light track vehicles using affordable thermoplastic based composites. FEM analysis with 3D modeling and simulation were identified as major designing tools for this project. Validation of the designed

model was done by fatigue life test of prototype samples with the help of biaxial wheel test bench.

1.2. Objectives

The aim of this project was to design a plastic rim for light industrial and commercial type vehicles using FEM analysis, modeling and simulation tools. The main objectives were formulated as follow:

- To design the rim structure capable to sustain the required load and to perform under service conditions.
- To develop a suitable manufacturing method emphasizing on material process ability, costing and process efficiency for serial manufacturing and commercialization.
- To identify the suitable thermoplastic composites taking into consideration of short and long term mechanical and thermal properties exhibited by materials during service life under dynamic loading.
- To estimate suitability of using software for designing the plastic rim by testing the prototype samples and comparing obtained results with simulated ones.

2. Literature Review

2.1. Importance of using plastic components in automobile industry

Replacing metals with plastics is a viable option in automobile manufacturing industry. Some of the cars surveyed registered a four-fold increase in their use of plastics between the 1970s' and 1990s'. It is estimated that, on average, 100 kilograms of plastics replaces 200-300 kilograms of conventional material, reducing fuel consumption by 750 liters over a life span of 150 000 kilometers (6). Additional calculations across all cars suggested that use of plastics reduced fuel consumption by 12 million tons and reduces CO₂ emissions by 30 million tons per year in Western Europe alone. (7)

Plastics have been widely used in automotive industry to innovate safety, performance and fuel efficiency. Some examples of application of plastics in automotive industry are: High-density polyethylene (HDPE) employed in fuel tanks, polymethyl methacrylate (PMMA) used in lightening devises, screens and in some window parts., polybutylene terephthalate (PBT) used to make automotive connectors, polyurethane (PU), acrylonitrile butadiene styrene (ABS) and polyvinyl chloride (PVC) are some of the other major plastics (8)

The major advantages offered by replacement of metals with plastics are (9)

- lower overall cost
- low maintenance
- reduced noise and vibration
- simplified design
- lower weight
- high energy efficiency
- better chemical resistance

When it comes to plastics, engineering thermoplastics and high performance plastics have made great strides in replicating many properties of metals, without the drawbacks. Engineering and high performance polymers cover a wide spectrum of materials that are valued for their temperature resistance, strength, dimensional stability and chemical resistance in many demanding applications.

2.2. High Performance plastics

Thermal stability is a key feature of high-performance plastics. High service temperature can be reached by linking of aromatics like phenyl with oxygen and forming biphenyl ether groups or polyetheretherketone plastic (PEEK). PEEK polymers are obtained by step growth polymerization by the dialkylation of bisphenolate salts. The reaction is conducted around 300 °C in polar solvents (figure 1) (10).

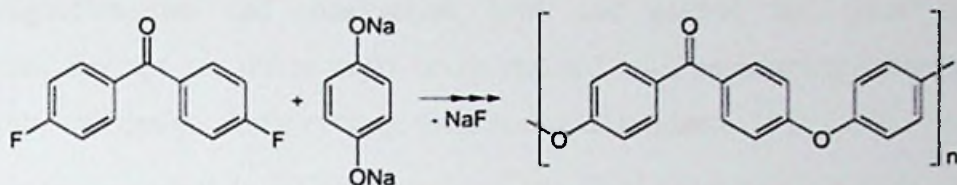


Figure 1 PEEK polymers
(11)

These plastics are of high strength, stiffness combined with toughness, high thermal and oxidative stability, low creep and transparency. The presence of aromatic elements and sulfone group provide resistance to heat and oxidation and display good dimensional stability, retain strength and dielectric properties during their service life. Polysulfones have low flammability (12).

Availability of nitrogen groups in plastics may improve strength together with thermal resistance (13). Example of such plastic is polyamide-imides (PAI). Polyamide-imides may be thermosetting or thermoplastic amorphous polymers that have exceptional mechanical, thermal and chemical resistant properties (13).

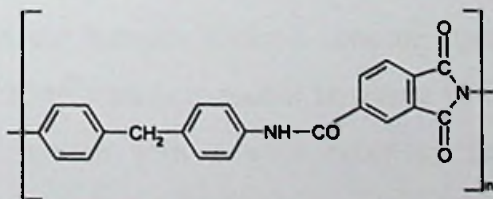


Figure 2 Polyamide-imides
(14)

In spite of a number of properties of high interest, some deficiencies were found in high performance plastics as, for example, predominantly poor metal adhesion. Further, in individual cases they possess poor stress cracking resistance. Moreover the industrial application of high performance plastics is hindered by higher prices and non-availability in larger quantities. As there is no success in current efforts such as

tailor made blends or surface modification these deficiencies contribute to a certain decline of high performance plastics as already observed in some cases (15).

2.3. Engineering thermoplastics

Acrylonitrile butadiene styrene (ABS), polycarbonates, polyamides are great starter materials and are affordable, durable and widely available. Engineering thermoplastics are used in every industry worldwide, primarily in the automotive, electrical or electronic, aircraft and aerospace, and plumbing; and in appliances, building/architecture and construction, lawn and garden, and other consumer products. Savings are increasingly being realized with engineering thermoplastics, with thin wall design; faster cycling; foam (cellular) products (16).

The use of less material; and higher strength-to-weight ratios compared to steel, brass, aluminum and other metals and ceramics and as an alternative to glass make engineering plastics very popular (12). Long-term, load-bearing applications at elevated temperatures and excellent electrical properties are special features of engineering thermoplastics. Non-load-bearing applications, such as wire enamels, and clear products such as windows, are gaining in use also.

New grades based on blends and alloys, fiber and mineral-filled composites, and application-specific formulations are continually being introduced (16). Uses of engineering thermoplastics are increasing for new products and as the preferred material-of-choice over metals.

2.3.1. Acrylonitrile Butadiene Styrene (ABS)

ABS is a terpolymer of acrylonitrile, butadiene and styrene. Usual compositions are about half styrene with the balance divided between butadiene and acrylonitrile. Considerable variation is, of course, possible resulting in many different grades of acrylonitrile butadiene styrene with a wide range of features and applications. Chemical structure is given in figure 3 (17).

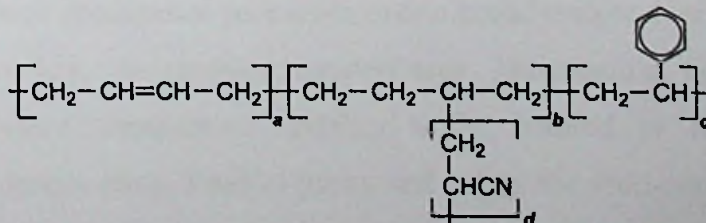


Figure 3 Acrylonitrile Butadiene Styrene

The effect of three monomers on properties can be seen from figure 4 in where acrylonitrile groups determine resistance to chemicals, strength, heat stability, and butadiene improves impact strength and flexibility at lower temperatures, while styrene gives rigidity and process ability.

ABS is engineering thermoplastic resin and can often meet the property requirements at a reasonable price. ABS is considered the best of the styrene family. It is tough, hard and rigid and has good chemical resistance and dimensional stability. As disadvantages limited weathering resistance, moderate heat, moisture and chemical resistance have to be mentioned (18).

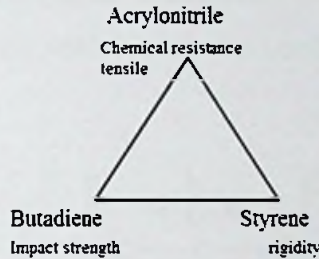


Figure 4 Styrene rigidity vs. processibility

2.3.2. Polycarbonate

Bisphenol A (BPA)–based polycarbonate (PC) is one of the most versatile and widely used engineering thermoplastics on the market. It is produced commercially by melt esterification process and phosgenations as per reactions below in (figure 5) and (figure 6) (19).

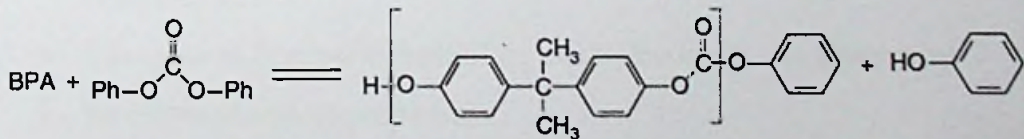


Figure 5 Esterification process
(19)

This amorphous material offers Outstanding impact strength—even at low temperatures, Good mechanical properties over a broad temperature range, Excellent dimensional stability, at elevated temperatures ,Outstanding optical properties ,Natural water-clear transparency ,Ability to be colored to form transparent, translucent, or opaque parts, Product purity and safety for food-contact and medical applications

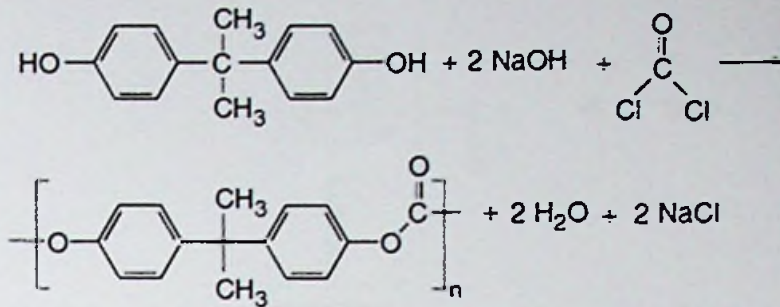


Figure 6 Phosgenation
(19)

2.3.3. Polyethylene Terephthalate (PET)

PET is a thermoplastic from polyester group. The basic building blocks of PET are ethylene glycol and terephthalic acid, which are combined to form a polymer chain (figure 7).

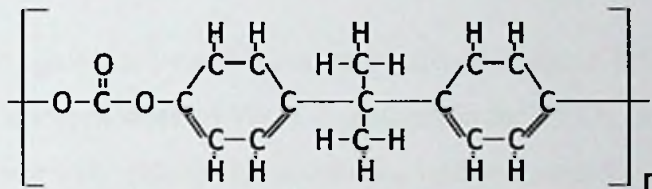


Figure 7 PET
(20)

Typically properties in which polyesters differentiate themselves from other engineering plastics are:

- Extreme low water absorption, in particular comparison to Nylon (Polyamides)
- Exceptional dimensional stability, due to the low water absorption
- Excellent electrical properties.
- Excellent resistance to chemical attack and high environmental stress crack resistance
- Very good heat and heat ageing resistance.
- Very low creep, even at elevated temperatures.
- Very good colour stability.
- Excellent wear properties

The major disadvantages of PET are high susceptibility to hydrolysis (figure 8) at elevated temperature. Addition of 0.06% of water to PET will sufficient to reduce molecular weight twice making plastic brittle (20).

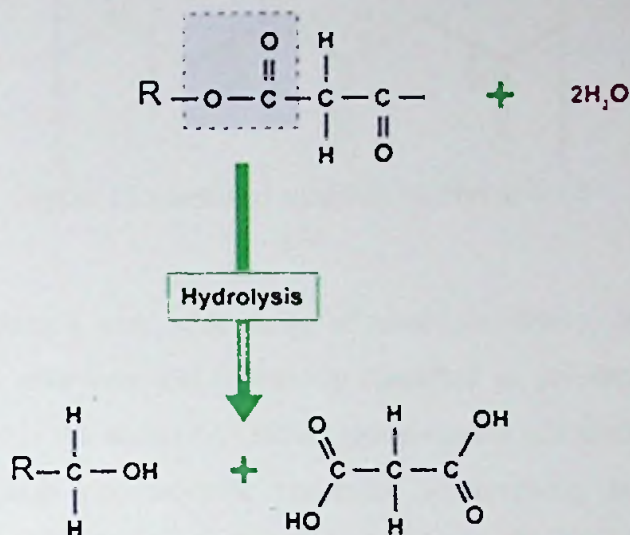


Figure 8 Hydrolysis of PET
(20)

2.3.4. Nylons

Polyamide (Nylon) polymer was first commercially introduced by DuPont as a result of the significant research work of W. H. Carothers in the 1930s, who was conducting early extensive research efforts in polyesters and polyamides (nylon). The first important polyamide was Nylon 6/6 produced by the reaction of adipic acid (a 6-carbon dibasic acid) and hexamethylene diamine (a 6-carbon aliphatic diamine). Several structural modifications with differing temperature capabilities have become commercially available including Nylon 4/6 (figure 9), Nylon 6/10 (figure 10), Nylon 6/12 (figure 10) etc... (9)

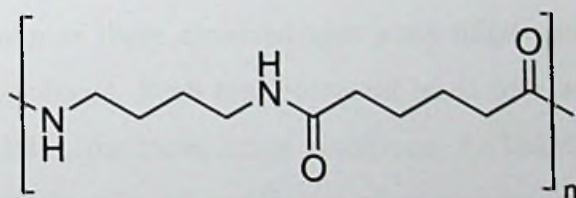


Figure 9 Chemical structure of Nylon 4/6
(9)

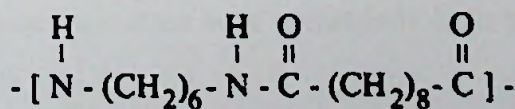


Figure 10 Chemical structure of Nylon 6/10
(9)

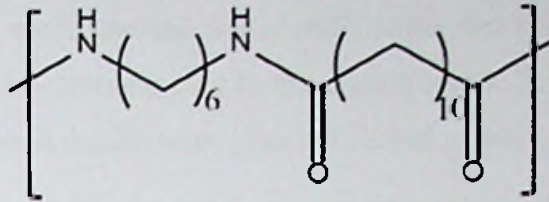


Figure 11 Chemical structure of Nylon 6/12
(9)

According to definition a very wide range of materials -fibers, crystalline plastics, amorphous plastics, adhesives and rubbers is classified as polyamides (nylon). The common feature that is the amide (-CONH-) group occurs repeatedly in the polymer. Such an amide group can increase resistance to swelling and dissolution in hydrocarbons, increase inter-chain attraction and hence stiffness and heat deformation resistance, reduce electrical insulation resistance, particularly at high frequencies. There are also a number of properties in which the nylons show up to a disadvantage when compared with metals (21). These include:

- Low rigidity and tensile strength.
- Dimensional instability due to a high temperature coefficient of expansion and high water absorption.
- Low impact strength to fracture.
- Low maximum service temperature.
- Low creep resistance.
- Low hardness and scratch resistance (9)

In an attempt to minimize these disadvantages glass-filled varieties of nylons have been successfully introduced. Such reinforcement leads to a substantial increase in tensile strength, modulus, hardness, creep resistance, ASTM deflection temperature under load and a sharply reduced coefficient of expansion. The glass-fiber nylons have a resistance to creep at least three times as great as unfilled polymers. These materials are distinguished by high thermo stability and resistance to hot lubricants and hot water. Parts made from them have particularly high dimensional stability and creep strength (9).

The yield stress of dry, unreinforced Nylon 6 ranges from 70 to 100 MPa while that of the same reinforced with 30% glass fibers grades rises as high as 250 MPa. The high melting point of glass reinforced nylon increases injection molding temperature that leads to a high solidification temperature and shorter cycle times. However, in glass-

filled grades the more rapid cooling and crystallization can lead to a poorer surface finish than obtained with corresponding Nylon 6 compounds. It is also considered that abrasive wear on screws is greater with glass reinforced nylon.

Water absorption of glass filled nylon decreases with increasing glass-fiber content. Depending on the moisture content, dimensional changes may also occur. The expansion of nylon due to moisture absorption is approximately 0.15 to 0.20 percent per 1 percent absorbed moisture. In normal ambient conditions (21°C, 50 percent RH) cast nylon absorbs 1.5 to 2 percent moisture to a depth of 0.040" to 0.080" over the course of approximately 40 days (9).

Additionally to that nylons are susceptible to hydrolysis and oxidation. Other investigators (22) found that unreinforced Nylon 6/6, for example, is not suitable for long-term exposure to 100% relative humidity at temperatures of 66°C (151 °F) or above. However, the strength of unreinforced nylon 6/6 was substantially reduced by long-term aging at 93 °C (200 °F), even at 0% relative humidity, indicating oxidative degradation of the plastic. Adding glass and stabilizers substantially improves the performance of nylons in hot/humid environments (22).

Nylons that absorb less moisture retain their properties longer under hot/humid conditions. Nylon 6/12 loses approximately one-third of its strength because of absorbed water; however, further decreases, even at 66 °C (151 °F), were found to be quite small (22). At 93 °C (200 °F), glass-reinforced Nylon 6/12 should be serviceable after 10 months at 100% relative humidity.

Izod impact strengths are similar; with unfilled nylons giving marginally higher values for glass reinforced ones. The above comments refer to comparisons between the two compositions at the same glass-fiber level. If, however, comparison is made between a nylon 6/6 composition with a glass content of x% and a Nylon 6 compound with a glass content of (x + 5)%, then the differences in mechanical properties become very small. At the same time the Nylon 6 material will have slightly easier processing characteristics and surface quality (9).

2.4. Type of glass fibers used for nylon reinforcement

Size of reinforcement fibers can either be short (1-2 mm) or long (5-20 mm) (figure 12). Mechanical properties are improved as length increases for short-length fibers it is vice versa. Fibers are usually in the form of continuous roving's, woven fabric, yarn

and mats of various combinations. The reinforcing element may also be in the form of particles and flakes. They may be aligned either longitudinally, transversely or scattered throughout the matrix (21).

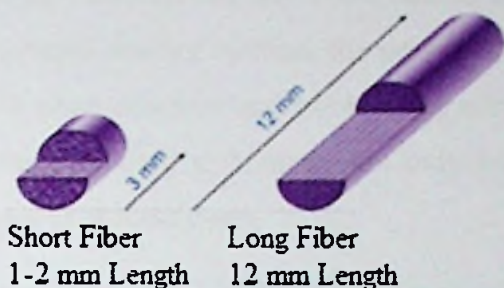


Figure 12 Short and long glass fiber

Short fibers are less effective than long ones and their characteristics are far more dependent on time and temperatures (23). Long fibers provide better load transfer through the matrix and are therefore used for critical condition and temperatures. A critical factor in reinforced plastics is the strength of the bond between the fiber and the polymer matrix, since the load is transmitted through the fiber-matrix interface. Weak bonding causes fiber pullout and delamination of the structure. Adhesion at the interface can be improved by special surface treatments, such as coatings and coupling agents. The advantage of short fibers is easier processibility and hence possibility of using conventional injection molding and extrusion machines for making products out of short fibers reinforced plastics. Short fibers reinforced nylon is compounded by traditional technology as shown in figure 13 (24). As glass fibers are not melted, they are fed into melting zone of mixing extruder. After passing pelletizing die number of filaments moves through the cooling both to granulator that cuts continuous filaments into granules of desire size.

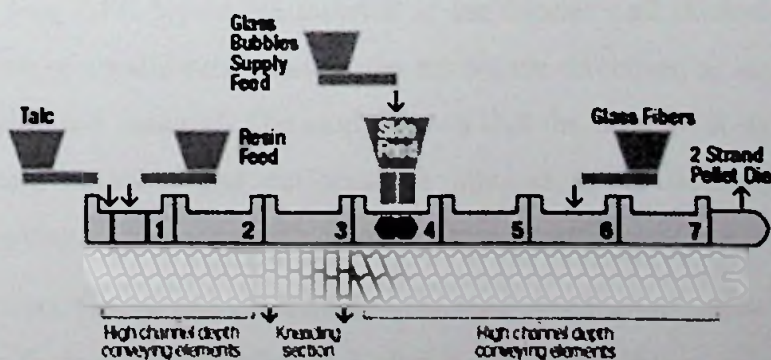


Figure 13 Compounding of short fiber nylon (24)

Long fibers are badly flowing additives into the extrusion process. This can lead to bridges, process interruptions or undesirable deviations in the formulation. With high performance compounding technology continues glass fibers material is coated with nylon when passing extruder die, coated fibers are cooled and cut as in figure 14. Compared with the old premix feeding method, the new process allows formulations with reduced damages in fiber structure and trouble free compounding. This means that high performance compounding technology not only benefits productivity and quality but also contributes to process costs.

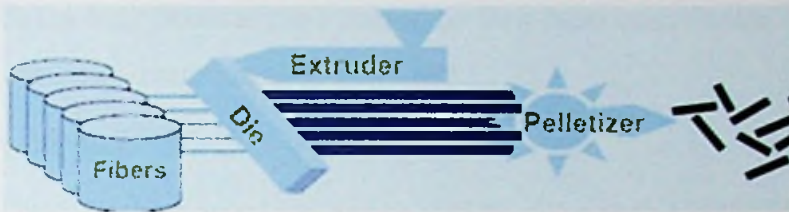


Figure 14 Coating of long glass fibers

Effect of fibers orientation on properties of parts made of glass reinforced nylons. The mechanical properties of glass fiber reinforced thermoplastics are affected not only by fiber length, but orientation within the skin and core regions of the molded objects. Since glass fibers orient and align themselves in the direction of flow the mechanical properties of fiber reinforced materials tend to be greater in the flow direction as compared to the transverse direction. In general, the 50% long glass fiber reinforced (GFR) Nylon 6/6 materials yielded a higher modulus and strength in the transverse and flow directions compared to the short GFR Nylon 6/6 resin. The long GFR Nylon 6/6 resin also exhibited comparable tensile properties in the flow and transverse direction at wall thicknesses of 3.2 and 4.4 mm (0.125 and 0.175 in). The greater core region in the long GFR Nylon 6/6 material at the thinner wall thicknesses results in higher retention of tensile properties in the transverse direction, as compared to the short GFR nylon 6/6 material. The study shows that the long GFR nylon 6/6 resins offer significant material and performance advantages in demanding structural applications, which will be subjected to biaxial stress conditions (25).

Static tensile tests, fatigue tests, and micro-structural observations show that injection-molded short E-glass fiber-reinforced Nylon 6/6 had significant anisotropy due to preferred composite were all higher in the flow direction than those normal to the flow direction. The presence of weld line caused a significant reduction in modulus, tensile strength, elongation, and fatigue strength of the material. The fatigue strength

of the material was also reduced by the presence of holes resulting in stress concentration. Both fatigue life and fatigue failure was affected by cyclic frequency. At frequencies 2 Hz, the failure mode of GF/PA 6, 6 was due to fatigue and the fatigue life increased with frequency. However, at frequencies 2 Hz, a combination of fatigue and thermal failures took place and the fatigue life decreased with increasing the frequency (26).

Generally the long fiber composites had better mechanical properties than the short fibers reinforced products (27). Short fibers are highly aligned in the mold filled direction while the long fibers aligned across the flow front contributing to better impact properties and greater material isotropy.

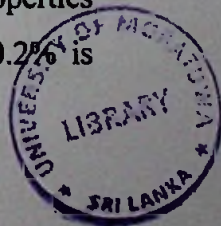
2.5. Nylon Processing

In the processing of nylons, consideration should be given to the following points; the tendency of the material to absorb water, the high melting point of the homo-polymer, the low melt viscosity of the homo-polymer, the tendency of the material to oxidize at high temperatures where oxygen, the crystalline of the solid polymer and hence the extensive shrinkage.

2.5.1. The tendency of nylon to absorb water

Nylons are sensitive to water due to the hydrogen-bond-forming ability of the amide groups. Water essentially replaces amide–amide–hydrogen bond with amide–water–hydrogen bond. Consequently, water absorption decreases with decreasing concentration of amide groups in the polymer backbone. Water acts as a plasticizer, which increases toughness and flexibility while reducing tensile strength and modulus. The absorption of moisture results in a deterioration of electrical properties and poor dimensional stability in environments of changing relative humidity. Therefore, care must be taken to reduce the water content of nylon resins to acceptable levels before melt processing to avoid surface imperfections and embrittlement due to hydrolytic degradation (28).

The nylon pellets exhibit a fast rate of water uptake in hot and humid environments. If pellets have absorbed water those pellets in a molding process could result in appearance problems such as silver streaking on the surface of the molded product and voids on the inside of the molded product, as well as sacrificed properties resulting from lower molecular weight. Water content of about 0.15% to 0.25% is



preferred in nylon pellets used in injection molding. To ensure proper water content levels in the injection molding of nylon it is necessary that the granules be dry. The polymer should be dried in an oven about 70-90°C. Too high a temperature will oxidize the surface of the granules and result in inferior moldings. Vacuum drying is the best means of drying nylon. Appropriate drying conditions are a temperature of 80-120°C and a vacuum pressure of 1013 MPa. Drying time should be 10 to 48 hours, depending on the pellet water content. Removing pellets from the dryer immediately after high-temperature drying and transferring the pellets to a container could result in oxidation or discoloration. Instead, reducing the temperature to below 70°C under vacuum before transferring the pellets is recommended. Vacuum-drying curve for nylon is given in figure 15. (29)

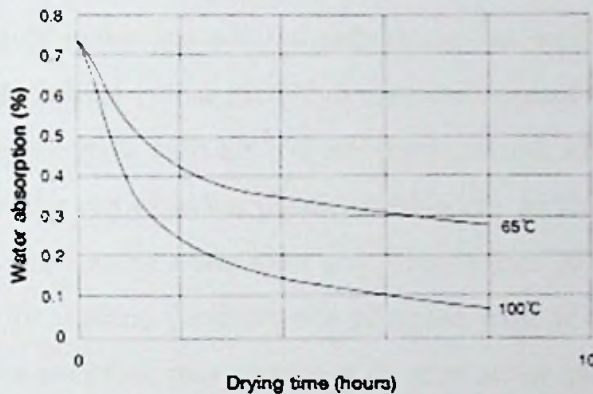


Figure 15 Vacuum-drying curve of nylon
(30)

To achieve better drying, is drying temperature and drying time can be increased. However, that the extent to which the drying temperature can be raised is limited by the risk of oxidation or discoloration. If an ordinary hot-air blow dryer is used the drying temperature should be no higher than 80-90°C to prevent oxidation or discoloration.

The high intermolecular attraction between amide groups leads to polymers of high melting point. Nylon6/6 melts at 255-265 °C, Nylon 6 melts at 210-220 °C. The high melting point gives it substantially greater safety margin for recovery from contact with hot objects. A higher melting point of nylon also provides resistance to frictional heating and its negative effect on wear performance. (31)

High temperature thermoplastics are known to retain their physical properties at higher temperatures and exhibit thermal stability even in the longer run. These thermoplastics therefore have higher heat deflection temperatures, glass transition

temperatures and continuous use temperature. Because of its extraordinary properties, high temperature thermoplastics can be used for diverse set of industries such as electrical, medical devices, automotive, aerospace, telecommunications, and many other specialized applications (32).

High melting temperature plastics show high level of toughness, strength, stiffness, resistance to fatigue and ductility. High melting temperature plastics show increased resistance to chemicals, solvents, radiation and heat, and do not disintegrate or lose its form upon exposure. Since high temperature thermoplastics have the ability to be remolded several times, they can be easily recycled and still display the same dimensional integrity and strength as before.

2.5.2. Nylon Injection molding

High melting point of nylon has some disadvantages as well. The major problem associated with high melting is that such high temperature accelerates oxidation. This means contact of nylon melt with air has to be minimized. For an example, in the extrusion of blown film out of nylon plastic, bubble has to be formed in the closed volume filled with nitrogen or other inert gas. This results in high processing cost. The ideal process for making products out of nylon melt is injection molding, as molten material does not come into contact with open air by means mold is properly ventilated and there is air trapped in the injection molding machine barrel (33).

Nylon Screw

- A screw for nylon applications in an inline screw injection-molding machine requires the following features:
- A short compression type shape is recommended. As shown in figure 16, the screw is divided into the following components: a supply section, a compression section and a measurement section. In particular, to be effective, the compression part should come immediately before the measurement part and be capable of compressing on a quarter- to a half-turn.
- A long screw ($L/D \geq 20$) is recommended.
- A compression ratio of 3 - 4 is adequate.
- Given the potential for wear, a material that is resistant to corrosion and wear, e.g., treated with a special lining, particularly
- When handling glass-fiber reinforced nylon (30)

Nylon screw

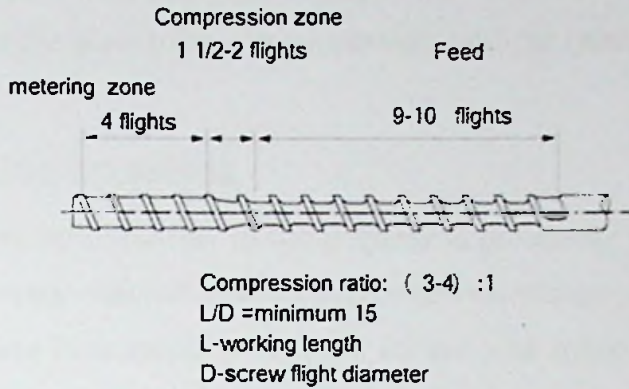


Figure 16 Nylon screw design
(30)

Barrel for Nylon Injection molding machine

Vented barrels are commonly used as a method of removing mainly moisture from hygroscopic materials. The basic concept involves melting the material through the first transition and metering section of the screw and then depositing the material into a decompression zone.

At this point, most of the moisture in the material is released from the barrel through a vent. The resin is then processed through a second transition and metering section prior to passing through the check ring assembly. Below is a sketch of a typical vented barrel configuration. If a vented barrel is selected, it is recommended to use a longer screw. Recommended L/D ratio for this application ranges from 26:1 to 32:1 (figure 17). The longer screw will facilitate producing a homogeneous melt. In addition, a hood placed above the vent is recommended to remove the volatiles from the molding facility.

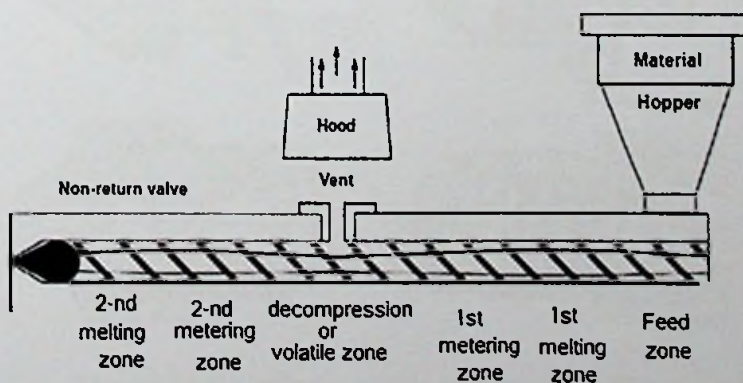


Figure 17 Barrel for nylon injection molding machine
(34)

Another related problem is above the melting point the melt viscosity of nylon is low because of the polymer flexibility at such high temperatures, which are usually more than 200°C above the glass transition temperature and the relatively low molecular weight.

Nozzle for Nylon Injection molding

Because of the low melt viscosity of the polymer at processing temperatures it will 'drool' through normal injection nozzles even when the plunger is retracted. Several types of nozzle have been specially designed for use with nylon and all function by sealing the end of the nozzle, either by allowing a pip of polymer to harden, by the use of spring-loaded valve, by the use of sliding side-closure nozzles or by the use of hydraulic nozzle valve activated at the appropriate stages of the molding cycle. Variations of this last approach have become popular since they are both positive in action and simple to operate. In designs in which solidified polymer is formed at the nozzle it is necessary to make provision for a cold-slug well in the mold, a feature frequently not possible with single-cavity tools. Where spring-loaded closing devices are used the spring should be kept as cool as possible if rapid thermal fatigue is to be avoided. Closed nozzles for nylon applications are given in figure 18 (34).

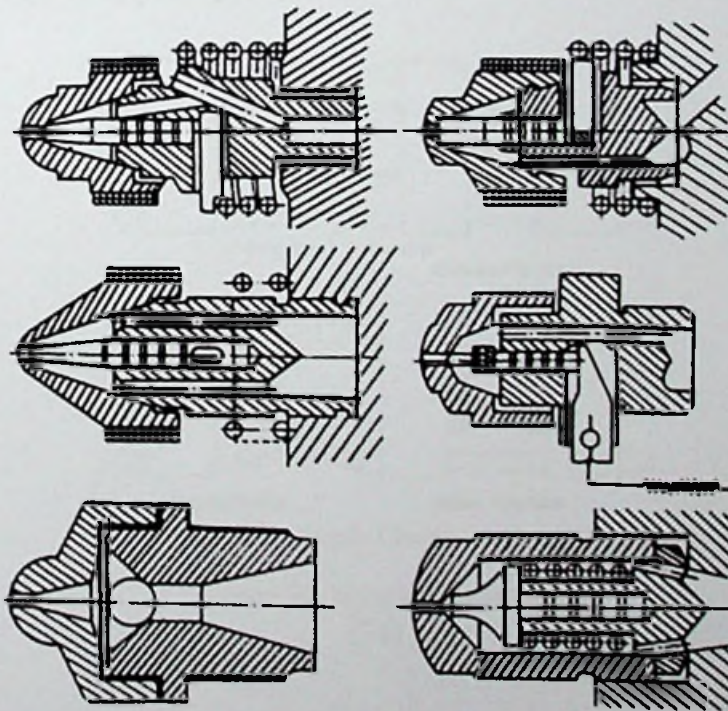


Figure 18 Nozzle for nylon injection molding
(34)

Compared to other resins, nylon has relatively low viscosity. During injection, back-flow of molten polymer could occur, so a screw head with a back-flow check valve such as that in figure 19 or non return ball valve figure 20 is needed. (34)

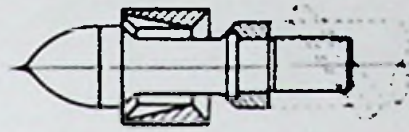


Figure 19 back-flow check valve nozzle
(34)



Figure 20 none return ball valve figure
(34)

Injection molding machine Clamping

Traditional clamping systems for injection molding machines fall into two main categories. These include the following types of clamps:

- i. Hydraulic Clamp (figure 21)
- ii. Toggle Clamp (figure 22)

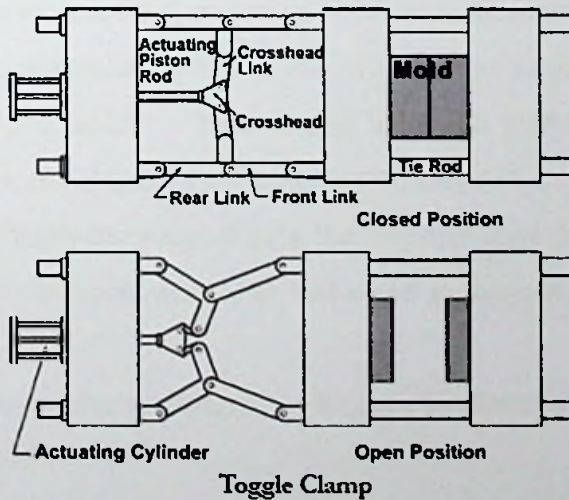


Figure 21 Hydraulic clamp
(34)

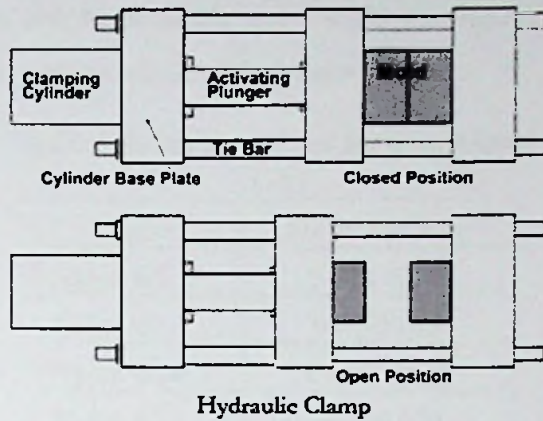


Figure 22 Toggle clamp
(34)

Toggle clamping is mainly used for high speed. Size of the mold and ejector mechanism can also decide in favor of toggle clamping.

There are advantages and disadvantages to each type of clamping unit based on equipment cost, ease of operation, speed, and maintainability. Toggle units are typically more energy efficient than ram units; however the energy used by the toggle clamping unit is small when compared to the energy used by the ram injection unit.

The differences between the two styles are

- i. Toggles generate tonnage via tie bar stretch
- ii. Hydraulics based on ram diameter and hydraulic pressure.
- iii. Toggle injection machines tend to increase tonnage as they run due to thermal expansion of the mold, tie bars, toggle links and plattens. Without a tie bar strain gauge, it is not known what the true tonnage is.
- iv. Hydraulics remains the same as long the pressure stays the same.
- v. Toggle machines open with near full close tonnage ratings. Great for deep draw parts.
- vi. Now with newer clamp designs, hydraulics is faster and more efficient than earlier one (34).

2.5.3. Shrinkage

All nylon molded part shrink. Shrinkage is the contraction of the molded part as it cools after injection. Typical shrink rates vary between 0.001/in/in and 0.020/in/in with the most common being around 0.006/in/in (35). Nylons are crystalline plastics and generally shrink more from the molten to solid state than do amorphous plastics this is a result of changes which occur in the structure as the polymer molecules orient

themselves to achieve the most stable solid state configuration. Typical shrinkage values for unreinforced nylons are in table 1 below (36).

Table 1 Typical shrinkage values for unreinforced nylons (36)

Type	Shrinkage in/in
Nylon 6/6	0.010-0.025
Nylon 6	0.07-0.015
Nylon 6/10	0.010-0.025
Nylon 6/12	0.08-0.020

Glass fibers as any other filler added to nylon normally reduce shrinkage. In general, linear mold shrinkage of glass reinforced nylons ranges from 50% to 90% less than that of unreinforced Nylons (37). Figure 23 shows effect of glass fibers content in Nylon 6/6 (Zytel 71), Nylon 6/12 (Zytel 77) and Nylon 6 (Zytel 70) (37) composition on shrinkage. There is significant reduction in shrinkage in both transverse and flow directions when fiber content increases in all nylons. However shrinkage in flow direction reduced significantly more when compared to transverse direction shrinkage (figure 23).

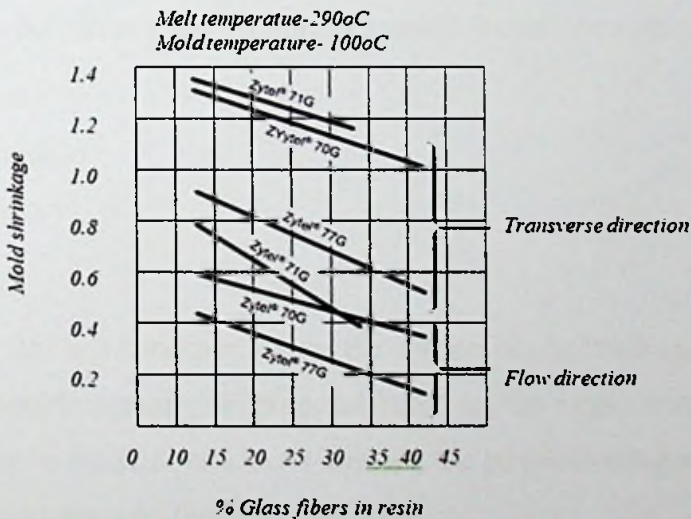


Figure 23 Effect of % Glass fiber in resin (37)

Other factors effecting on mold shrinkage are part thickness and processing conditions. Typical shrinkage values obtained with various wall thicknesses for an unfilled nylon are as follows in table 2. Processing conditions can have a significant effect on mold shrinkage. The following adjustments decrease mold shrinkage (37). Processing conditions can have a significant effect on mold shrinkage. The following adjustments decrease mold shrinkage, making the molded part larger:

- Reduce wall thickness
- Increase injection pressure
- Increase injection forward time
- Increase gate size
- Lower mold temperature
- Lower material temperature
- Increase injection speed
- Increase cycle time

Table 2 Wall Thickness vs. Mold Shrinkage
(36)

Wall Thickness, in.	Mold Shrinkage, in./in.
0.06	0.008 - 0.015
0.125	0.010 - 0.020
0.25	0.015 - 0.025
0.5	0.025 - 0.040

2.5.4. Injection Molding Defects

The most common defects of glass reinforced nylon injected parts are:

- Brittleness
- Discoloration
- Flow marks

Brittleness

Brittleness (figure 25) is a condition where the part cracks or breaks at a much lower stress level than would normally be expected based on the virgin material properties or it has a tendency to break or crack. As a result, the physical integrity of the part is substantially less than the specification. (38), (39)



Figure 24 Brittleness example
(38), (40)

Cracking, crazing, or brittleness is associated with process-related causes of stress in the part due to

- Fast injection
 - Excessive moisture
 - Excessive drying time
 - High trying temperature
 - Restriction to flow (40)
- Fast injection

Fast injection can lead to high molecular orientation, especially in thin-wall parts. These parts get cooled fast and highly oriented stressed structure is fixed giving no opportunity to molecular chains to relax and release stresses. (40)

- Excessive moisture

Moisture may significantly effect on appearance of this defect. Nylon melts at very high temperature and if it is wet with moisture content exceeding > 0.2% hydrolytic degradation occurs resulting in significant loss of physical properties. Hydrolytic degradation is a chemical reaction that occurs at high temperatures with some nylons in the presence of water. It causes primary bonds in the molecular chains to be severed, thus reducing molecular weight .Lower members of the nylons (such as Nylon 6) are affected more than higher members such as Nylon 6/12. Schematics of the reaction are given below in figure 26. (40)

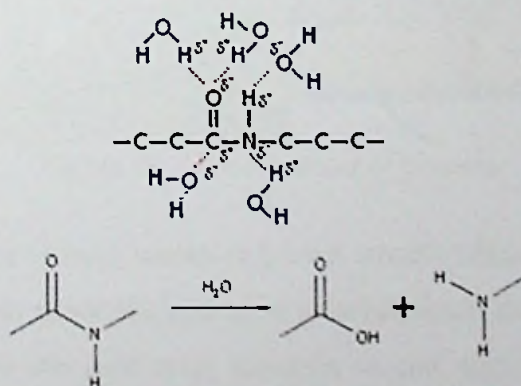


Figure 25 Hydrolytic degradation of Nylons 6 compared to Nylon 6/12

- High drying temperature and Excessive Drying

As molecular weight of the polymer reduced, it becomes brittle. Brittleness can be caused by excessive drying time or excessive drying temperature such as at full heat

for several days. Nylons are very sensitive to Excessive drying as they degrade reducing the molecular weight. (40)

- Restriction to flow in gate and runners

Gates and runners that are too small will cause restrictions to the flow of molten plastic. These restrictions cause the material to heat up due to shearing friction and the material will thermally degrade. This results in weak molecular bonding and causes the molded parts to be brittle. (40)

Discoloration

Discoloration can be defined as a change in the original color of a plastic material usually caused by overheating, mechanical shear, contamination, or chemical attack. The discoloration means the partial chemical change of materials contained in the moldings. Therefore the cause of discoloration must be pursued with each component. Nylons in general are composed of these five types of materials Polymer, Stabilizer, Pigment, and Filler. Stabilizer, Pigment, and Filler must withstand high melting point of nylon. Discoloration is similar to burn marks or brown streaks (figure 27) but generally not as dark or severe. It may cause the part to be a darker shade than the virgin pellets and is often found nearest the gate area; however it can also appear as dark streaks throughout the part.

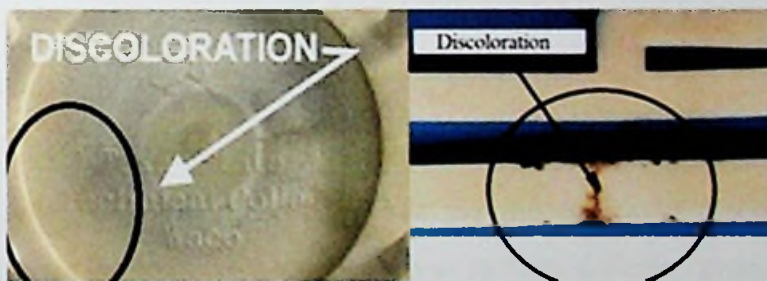


Figure 26 Discoloration of plastics
(41)

Discoloration is similar to burn marks or brown streaks (figure 27) but generally not as dark or severe. It may cause the part to be a darker shade than the virgin pellets and is often found nearest the gate area; however it can also appear as dark streaks throughout the part. The reasons for nylon part discolorations are:

- Long residence time
- Over drying
- Contamination

- Long residence time

Long residence time can be related to excessive shot size ratio. Ideally, a shot size should equal 50% of the capacity of the barrel. That results in processing one cycle while preparing for the next cycle. However, this is a general statement because, depending on the material, the ratio can be as small as 20% for non-heat-sensitive materials such as polypropylene, and up to 80% for heat-sensitive material such as PVC. As the ratio drops, the residence time of the material in the barrel increases so does the risk of thermal degradation. Degraded material will discolor due to the molecular breakdown. The material will start showing dark yellowing that progresses towards black as the degradation worsens. (41)

- Excessive cycle time

Excessive cycle time that is too long will increase the residence time for the material in the heating cylinder. The longer residence time may cause the material to begin to degrade and discoloration will occur as the material begins to carbonize.

Improper mold temperature .A hot mold will cause a molded part to be darker than if it had been molded in a cold mold. This is because the hotter mold allows the material molecules to pack tighter before they solidify and the part is denser. The colder mold causes the material to solidify before the molecules are packed tightly so the part is less dense (41).

- Contamination

If the raw material contains any contamination, such as dirty regrind, dust from storage areas, etc., the molded part will show varying degrees of discoloration based on the location and type of contaminant. Even mixing different grades of the same material or different flow values of the same material can cause differences in color (41).

Flow Marks

Flow lines can be defined as linear grooving, or circular ripples, on the surface of a molded part that indicate the direction of material flow within the cavity of the mold (figure 28).



Figure 27 Flow marks
(42)

- Low injection pressure

If too little injection pressure is used, the molten plastic will tend to cool down and solidify before the mold is packed out. If no packing is achieved, the flow pattern of the material will be imprinted on the surface of the part because not enough pressure was used to force the plastic against the steel of the mold and squeeze out the flow lines. Increasing the injection pressure will force the molten plastic against the mold cavity steel before the plastic solidifies; removing the flow lines and duplicating the cavity finish (42).

- Reduced residence time

Residence time is the amount of time that the plastic material spends being exposed to heating conditions in the injection barrel. The required time depends upon how much heat the material must absorb to be processed properly. Inadequate residence time results in under heated material. This will cause the material to be stiff when injected and it will not flow enough to fill the cavity before solidifying. The flow patterns will be imprinted on the surface of the molded part because they were not forced out in time. Optimizing the residence time by making sure the mold is sized to the proper machine. Also, optimizing the cycle time to ensure the material residence time is adequate to properly melt the plastic. (42)

- Low barrel temperature

Low barrel temperatures have the same effect as short residence time. The plastic material does not become fluid enough to fill the mold before solidifying and flow lines are imprinted on the part surface before they can be forced away.

Increase of the barrel temperature is recommended by the material supplier to adjust and eliminate the flow lines. Additionally to that the profile needs to set so the material is heated from the rear towards (40) the front of the barrel. (42)

- Low nozzle temperature

As material is transported through the heating barrel, it is gradually brought up to the ideal processing temperature by absorbing heat from the heating bands and frictional heat, which is created by the shearing action of the rotating screw within the barrel. In the last heating zone, the material is exposed to is the nozzle. By the time the material gets to the nozzle, it should already be at ideal molding temperature and only a small amount of heat needs to be applied at this point to keep the resin flowing. If the nozzle is not hot enough, however, the material will begin to cool off too quickly as it leaves the barrel and the flow front will not be forced against the cavity steel to squeeze out the flow lines. Increase the nozzle temperature. As a rule-of-thumb, the nozzle temperature should be set at 10 degrees F higher than the setting for the front zone of the barrel. This helps compensate for heat loss due to metal-to-metal contact between the nozzle and the sprue bushing, and keeps the material hot enough to pack the mold, eliminating flow lines. (42)

- Short cycle time

If the overall cycle time is too short there is a good possibility that the material in the barrel cannot absorb enough heat before it is injected into the mold. This will cause premature solidification and flow lines may appear because the plastic was not packed enough (before solidifying) to squeeze them out. Increasing the cycle time is the easiest change to make is to add time to the cooling portion of the cycle. That is when the plastic is absorbing the most heat in the barrel. Increase barrel temperatures 10 degrees F at a time, allowing 10 cycles between changes to re-stabilize the process. (42)

- Low mold temperature

A hot mold allows a material to stay molten longer than a cold mold and cause the molecules to pack together properly before they solidify. This results in a dense part with no flow lines. If the mold is too cold, the molecules solidify before they are packed out and flow lines may result. Mold temperature should be increased to the point that the material has proper flow and packs out the mold. (42)

- Improper venting

If there is not enough venting in the mold, the material will push into unvented areas and not compress against the mold steel because trapped gases are in the way. The material will actually "stutter" as it tries to force the gas out of the way, and will eventually solidify before packing can be achieved. The stutter marks will imprint on the part surface as flow lines. Vent the mold by grinding thin (0.0005"-0.002") pathways on the shutoff area of the cavity blocks. The viscosity of the plastic being molded determines the depth of the vent. Stiff materials can utilize deeper vents but fluid materials require thinner vents. In either case, the concept is to remove air from the mold as fast as possible with as deep a gate as the material viscosity will allow. At least 30% of the parting line perimeter should be vented, but additional vents can be selectively placed for any area where flow lines appear. (42)

- Small gates and runners

Gates and/or runners that are too small will cause excessive restriction to the flow of the molten plastic. Many plastics will then begin to solidify before they fill the cavity. The result is an unpacked condition of the molecules and flow lines will not have a chance to be pressed out of the product surface. The gates and runners are examined to determine if any burrs or other obstructions exist. It is recommended to perform a computer analysis to determine the proper sizing and location of gates and runners. It is recommended to ask material supplier for data concerning gate and runner dimensioning for a specific material and flow rate (42)

Resin manufacturers supply specific formulations in a range of standard flow rates. Thin-walled products may require an easy flow material while thick-walled products can use a material that has a stiffer consistency. It is better to use the stiffest flow possible because it improves physical properties of the molded part. However, the stiff material will require higher injection pressures, which may blow the mold open and cause flash at the parting line. If an easy flow material is used, the physical properties will not be as great but, in addition, the material will flow into very thin areas and could create flash where the stiffer materials would not.

Utilization of material that has the stiffest flow is also possible without causing non-fill. It is recommended to contact the material supplier for help in deciding which flow rate should be used for a specific application. (42)

- Inadequate mold lubricant

If a material is too stiff, it may solidify before packing the cavity and flow lines could exist. A lubricant can be added to improve the flow. If this is an external lubricant such as a mold release agent, it is difficult to control the amount of lubricant being used and the material may more fluid than required. The result could be flashing where the material would not do so without lubricant. If it is determined that a lubricant must be used, have the material manufacturer (or a compounder) add it directly to the pellets. That will result in more uniform blending and all the material will have the same flow rate. (42)

2.6. Design of plastic components

When designing thermoplastic components, generally following points need to be considered:

- Nominal Wall thickness
- Uniform wall thickness
- Corners design
- Coring design
- Draft and texture design
- Structural reinforcement design

2.6.1. Nominal Wall thickness

Wall thickness strongly influences many key part characteristics, including mechanical performance, appearance, mold-ability, and economy. The thinner the wall the faster the part cools and cooling time is proportional to square of wall thickness. Large cooling time for solid will increase molding cycle, reduce production rate and increase product cost.

Thicker section shrinks more than thinner section and introduces warpage or sink marks. The wall thicknesses of an injection-molded part generally range from 2 mm to 4 mm (0.080 inch to 0.160 inch). Thin wall injection molding can produce walls as thin as 0.5 mm (0.020 inch). But this needs special expensive technique. Minimum wall thickness is related to part stiffness, while upper limit affects cooling time. There some experimental data available for selection of nominal wall thickness for injection molded part depending on plastic used (table 3).

Table 3 Nominal wall thickness for thermoplastics

Thermoplastic resin	Typical thickness ,inches
ABS	0.045-0.14
Acetal	0.03-0.12
Long fiber reinforced plastic	0.075-1.00
Nylon	0.01-0.115
Polyethylene	0.03-0.200
Polypropylene	0.025-0.150
PVC	0.04-0.150
polyester	0.025-0.125

If the wall thickness is above the maximum recommended, sink marks or voids may appear. A sink mark is a local surface depression and a void is a vacuum bubble in the core (figure 29). After the material on the outside has cooled and solidified, the core material starts to cool. Its shrinkage pulls the surface of the main wall inward, causing a sink mark. (43) (44)

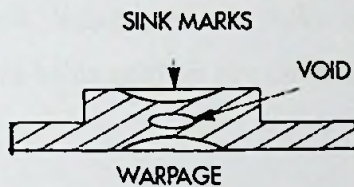


Figure 28 Sink Mark
(43)

2.6.2. Uniform Wall thickness

The basic rule for plastic part design is to keep wall thickness as far as possible uniform or constant throughout the part. Thick sections cool slower than thin sections. The thin section first solidifies, and the thick section is still not fully solidified. As the thick section cools, it shrinks and the material for the shrinkage comes only from the un-solidified areas, which are connected, to the already solidified thin section. This builds stresses near the boundary of the thin section to thick section. Since the thin section does not yield because it is solid, the thick section (which is still liquid) must yield. Often this leads to warping or twisting (figure 30). If this is severe enough, the part could even crack. (44)

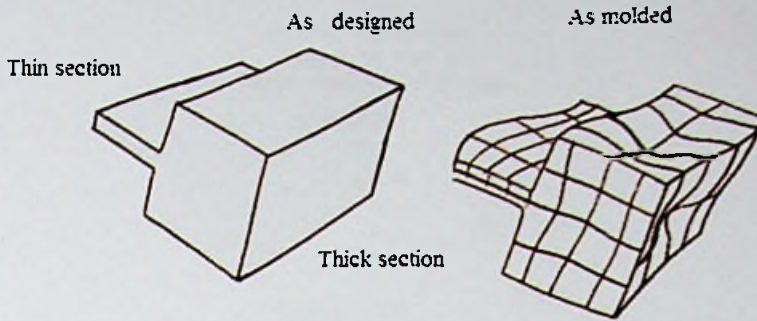


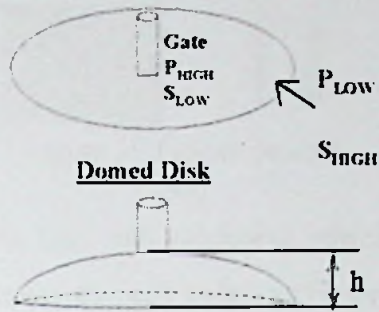
Figure 29 Warping and twisting
(45)

Plastic shrinks as it cools which can lead to defects such as, stresses, and warping. Plastic resin solidifies in the mold nearer to the outside of the part (closest to the mold surface). Thick sections of a part tend to pull inward, creating stresses, sink marks, or voids. Since thinner sections cool quicker, stress can build in the part between thinner and thicker sections, resulting in part warpage. Mathematical definition of the warpage is a height of a domed disk (h) formed out of flat plate (figure 31). Uniform walled parts are easier to fill in the mold cavity, since the molten plastic does not face varying restrictions as it fills. When uniform walls are not possible due to design limitations, the change should be as gradual as possible. Some of examples are shown in (figure 32) (43).

2.6.3. Corners

When two surfaces meet, it forms a corner. At corner, wall thickness increases to 1.4 times the nominal wall thickness. This results in differential shrinkage and molded-in stress and longer cooling time. Therefore, risk of failure in service increases at sharp corners. Sharp corners greatly increase the stress concentration. This high amount of stress concentration can often lead to failure of plastic parts. The stress concentration factor varies with radius, for a given thickness (figure 32) (46).

**Center-Gated Disk:
Warpage Due to
Nonuniform Shrinkage**
Flat Disk



Domed Disk



Figure 30 Mathematical definition of warpage
(45)

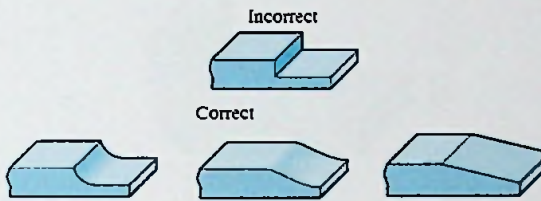


Figure 31 Correct design of sharp corners
(39), (43)

Corners designed without radii can cause stress concentrations. These in turn may reduce the ability of the part to withstand load and/or cause warping in its geometry. Sharp corners might adversely affect the flow of resin during molding, potentially causing incomplete fill. They also tend to cause the part to stick to the mold during ejection, which can cause a variety of problems. Actual Stress in the plastic is calculated as a product of Stress Concentration Factor K and normal Stress. (45), (46)

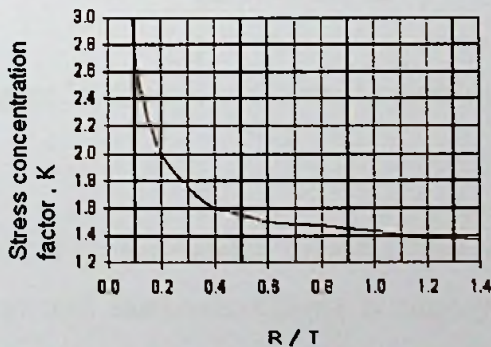


Figure 32 of Stress concentration factor K and normal Stress
(45)

Sharp corners might adversely affect the flow of resin during molding, potentially causing incomplete fill (figure 33). They also tend to cause the part to stick to the mold during ejection, which can cause a variety of problems.

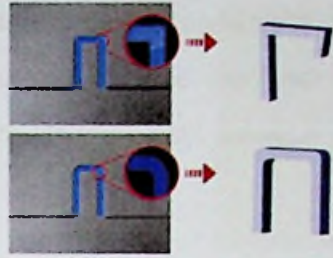


Figure 33 Corner design
(46)

Usually the outside radius is one wall thickness larger than the inside radius to maintain constant wall thickness through corners (figure 34). Internal and external corner radii should originate from the same point. (46)

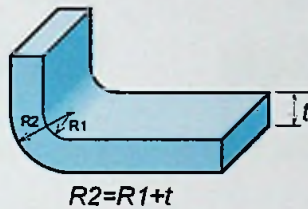


Figure 34 Calculation of outside radii of corner design
(46)

Examples of correct corner's design or how to avoid increase of thickness at corners are given below in figure 35.

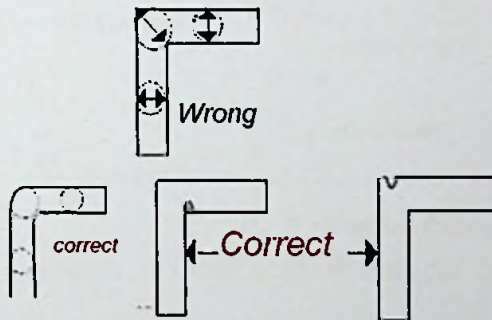


Figure 35 Examples of correct corner design
(45)

2.6.4. Coring

Coring means a Removal of excess material from the cross section of a molded part to achieve a more uniform wall thickness. Coring is employed as the shape forming process step, part designs can avoid the limitations of traditional metalworking processes. For example, machining involves the removal of material from a solid shape to get to the desired final component design. As a result, the benefits of removing excess material for reduced part mass are generally not considered for metals as this design approach would add incremental machining costs. In the case with plastic injection molding, design engineers can do it. This serves several benefits

for the process and the customer. Any opportunity to limit the amount of material required in a component helps minimize the final part cost. Figure 36 illustrates several preferred geometries accomplished through coring to create uniform walls (45).

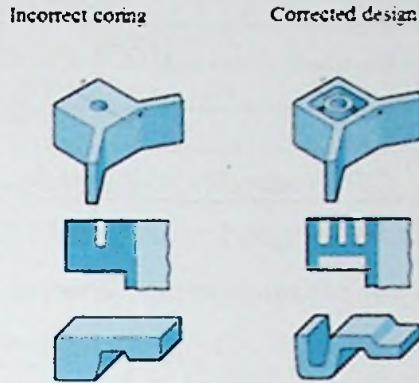


Figure 36 Geometrical techniques to have uniform wall thickness (46)

2.6.5. Draft and texture design

Draft angles are almost always necessary for any vertical wall of an injection molded product. Draft angles will ease the part's ejection from a mold (figure 38).

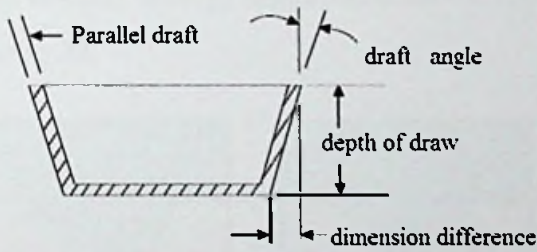


Figure 37 Draft angel definition

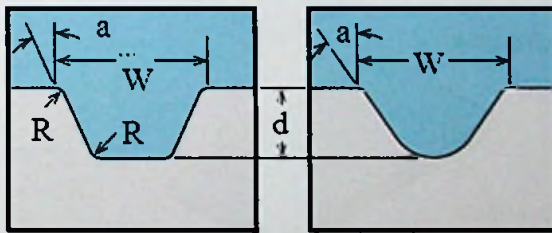
Draft angles typically range from a fraction to several degrees. Draft angles are depended on depth of draw, material rigidity and shrinkage, surface lubricity, and mold surface roughness. Recommended draft angles for plastics are given in table 4. (45)

Table 4 Recommended draft angle for plastics
(46)

Plastic type	Draft angle
Polycarbonate (PC)	1-2°
Polystyrene (PS)	> 0.5°
Polyarylsulfone (PSU)	1-2°
Polyarylethersulfone (PES)	1-2°
Polypropylene (PP)	>0.7°
Polyethylene (PE)	>0.7-0.8°
Acrylonitrile/ Polybutadiene/ Styrene (ABS)	1-1.5°

For un-textured surfaces, 0.25 degrees to 2 degrees per side for both inner and outer wall is usually sufficient. In certain applications the use of draw polish on the mold surface may allow a smaller angle.

Textures and lettering can often be molded into the surface of a part. This can be very helpful in that it can serve as an aesthetic or decorative surface at no additional cost. It can also help to hide surface imperfections such as weld lines. Textured side walls require an additional 0.4 degrees draft per 0.01 mm depth of texture, though each individual case should be discussed with the mold texturing supplier. For larger drafts, up to as much as 10 degrees may Design suggestions for the cross-sectional profile of lettering is shown in figure 39.



$$a > 30 \circ \quad W > 2d \quad d = 0.01 \text{ in (Max.)}$$

Figure 38 Method to add drafts for draft angles over 10 degrees
(46)

2.6.6. Structural reinforcement design

The major component of designing for structural integrity, in many cases, is to design the structure to be stiff enough to withstand expected loads. Increasing the thickness to achieve this is self-defeating, since it will: (46)

- Increase part weight and cost proportional to the increase in thickness.
- Increase molding cycle time required to cool the larger mass of material.
- Increase the probability of sink marks.

If the part is subjected to any significant loading, its load-carrying ability or stiffness can be increased either:

- By selecting more stronger plastic material with higher modulus or
- By improving the section properties of the structure i.e. The moment of inertia and the section modulus.

Selecting the stronger plastic with higher modulus may increase product cost and may be not sufficient. Improving section properties is the easiest solution for increasing the load bearing capability of plastic parts. The use of ribs is an effective way of achieving rigidity and strength, while avoiding heavy cross-sectional thickness. If greater stiffness is required, the spacing between ribs can be reduced enables to add more ribs.

If sufficient space is available, the use of ribs is a practical and economical means of increasing the structural integrity of the injection molded part without creating the thick walls. The efficiency of the ribbed structure can be seen from the examples described below (figure 40).

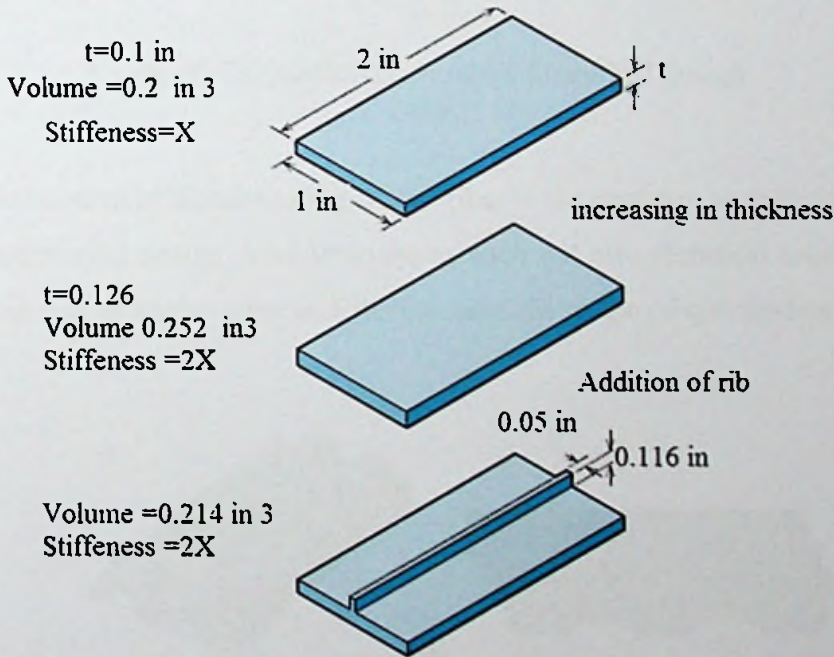


Figure 39 Efficiency of ribbed structure
(46)

In this example, adding a rib to double stiffness increases part volume by only 7% as compared to 25% when the part thickness is increased. Well-designed ribs can overcome these disadvantages with only a marginal increase in part weight. Certain

guidelines in designing the rib should be followed to avoid excessive thickness resulting in sinks on the opposite surface whereas small thickness and too great a draft will thin the rib tip too much for acceptable filling. Ribs should be tapered (drafted) at one degree per side. Less draft can be used, to one half degree per side, if the steel that forms the sides of the rib is carefully polished. The draft will increase the rib thickness from the tip to the root, by about 0.175 mm per centimeter of rib height, for each degree of draft angle. The maximum recommended rib thickness, at the root, is 0.8 times the thickness of the base to which it is attached. The typical root thickness ranges from 0.5 to 0.8 times the base thickness. Recommended design parameters for the ribs are given in figure 41. (46)

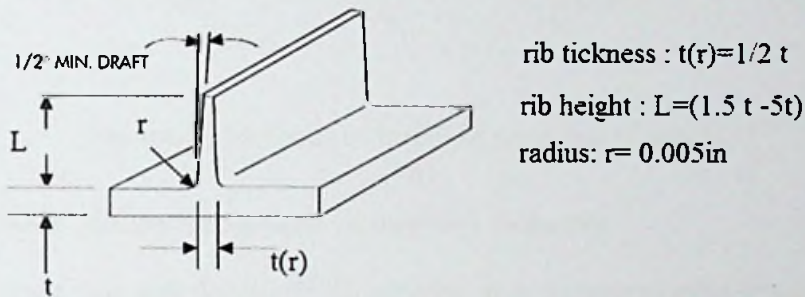


Figure 40 Calculation parameters for ribbed design (46)

Generally for optimum dimensioning of the ribs, it is necessary to take into account not only engineering design considerations as such but also technical factors relating to production and aesthetic aspects. Ribs can take the shape of corrugations figure 42 (1).

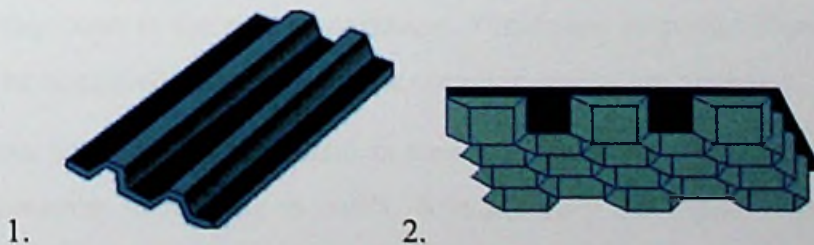


Figure 41 1.Corrugated structure 2. A hexagonal array of interconnected ribs (45)

The advantage is that the wall thickness will be uniform and the draft angle can be placed on the opposite side of the mold, thereby avoiding the problem of the thinning rib tip. A hexagonal array of interconnected ribs will be more effective than a square

array, with the same volume of material in the ribs. Honeycomb ribbing attached to a flat surface provides excellent resistance to bending (figure 42) (2). Besides above there are other acceptable methods of improving section properties .Many of these can often be worked into functional or appearance features of the part. Some typical examples are shown in figure 43.

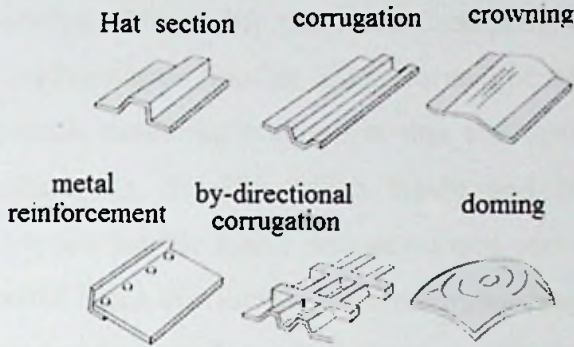


Figure 42 Methods to improve sectional strength (46)

2.7. Application of simulation tools in polymer industry

SIMUL8 Corporation has described Simulation as a computer model that mimics the operation of a real or proposed system for a discrete event similar to day-to-day operation of a bank or running of an assembly line in a factory or even staff work assignment of a hospital or call center (47). Simulation is time based and takes into account all the resources and constraints involved, as well as the way these things interact with each other as time passes. Simulation builds in the randomness as similar that of in real life; hence any change in the system will reflect same as that of in real life. Using simulation software makes it possible to test out ideas at a fraction of the cost than trying them in the real organization. Simulation is quick. Therefore many changes can be simulated and seen until the optimum results are obtained.

Simulation can be described successful in case it is based on cost, repeatability and time. Experimenting in real life is costly. It is not only the capital expenditure of hiring new staff or purchasing new equipment it is the cost of the ramifications of these decisions. In real life it is really difficult to repeat the exact circumstances again therefore chance to collect the results and test different ideas under the exact same circumstances is practically is not possible. With simulation it is possible to go years into the future in seconds but in real life waiting for many years to get the results which are expensive and impractical. Recently simulation tools have been found wide

applications in vehicle rim and complete wheel design. For an example Static fatigue test can be seen in seconds without waiting for years (48).

Since the 1970's several innovative methods for testing wheels were initiated. In recent years, the testing procedures have been improved by a variety of new experimental and analytical methods for structural analysis (49). During past 10 years period, durability analysis, fatigue life predication and reliability methods have been applied to the automotive wheel. Another test performed on wheel before going it into production is a dynamic cornering fatigue test that was successfully simulated and tested by P. Meghashyam, S. Girivardhan Naidu and N. Sayed Baba (50). A parametric representation for the forces was developed and showed analytically by them. Upon successful Force distribution from study, loading conditions as required by standards for cars and for truck/bus wheel rims were simulated.

Standardized testing protocols for composite materials mainly target the following two options by National Research Council stated that (51). Those options are:

- i. Modeling and simulation to verify and validate plastic/composite crash safety structural, semi-structural applications validate plastic/composite material choices in safety applications.
- ii. Demonstrate integrated safety performance for prototype to enable commercial deployment Industry crash-test and self-certify safety. (51)

The electronic vehicle (EV) car rim and tire were simulated by A. Kulkarnia and A.Kapoor (52) to have the maximum weight optimization in order to obtain the maximum range of charged battery. The study was conducted on 5 differently designed wheels. The Simulation results were collected in 5 areas which were of main concern such as structural rigidity, the thermal stability, and the life cycle assessment, deflection and stress distribution and those data were successfully confirmed by testing of real wheel as per appropriate standards.

Development and evaluation of the durability of plastic worm wheel for reduction gear in compact and family sedan vehicles were illustrated by J.W. Lee and T.S. Ill (53). According to the article plastic worm wheels had poor properties compared to those of metal materials in terms of strength and hardness. Therefore Plastic gear wheels (figure 44) are advantageous in terms of light weight, low vibration, noise reduction, and corrosion resistance.

Tooth like worm wheels (figure 45) (53) were modeled and simulated. The designing of these wheels was followed with a structural analysis and injection molding simulation Computer aided engineering (CAE) analysis and finally wheels structures were optimized in a such a way that tested in real life helical-type worm wheel showed relative advantageous in terms of the maximum stress and strain compared to steel one.



Figure 43 Helical worm wheel
(53)



Figure 44 Tooth like worm wheel
(53)

CAE analysis helped to identify that the worm wheel of 50 wt % glass fiber reinforcement content was advantageous in terms of deformation (53), which had a great effect on the operation of the worm wheel in terms of deformation. Deformation was considered to be the main factor for plastics effecting on the operation and performance. Finally it was also possible to study effect of glass fibers content in plastic composite on strength and hardness which were potentially improved, but increased damage caused by impact due to increased brittleness.

CAE analysis showed that the poor properties were caused by the fact that distributions of glass fibers were not even and unevenly distributed fibers were found in the worm wheel teeth. The uneven distribution of the glass fibers resulted in non-uniform strength and hardness of the worm wheel teeth. Based on these results

molding techniques was re-designed and implemented uniquely this product to ensure secure stable reinforcement distribution and orientation of glass fibers.

Modeling of the wheel using latest simulation software opens new possibilities for structural design, material selection and designing correct tools for manufacturing quality products in terms of performance, reduction of manufacturing cost, safety and durability.

2.8. Finite Element Analysis

FEM is a numerical method that is used in solving problems in engineering and metaphysics, and is also referred to as Finite element analysis (FEA). FEA is the modeling of products and systems in a virtual environment, for the purpose of finding and solving potential (or existing) structural or performance issues (5). FEA is applied to a solid object, especially to an interior of an object that has known mechanical properties (54). The solid body is represented by equal triangular shapes. The ends/common edges are called as “Nodes” and the area or space between nodes is called as “Elements”, and hence the combination that represents the nodes and elements of a solid body is called as mesh (Figure 46) (54).

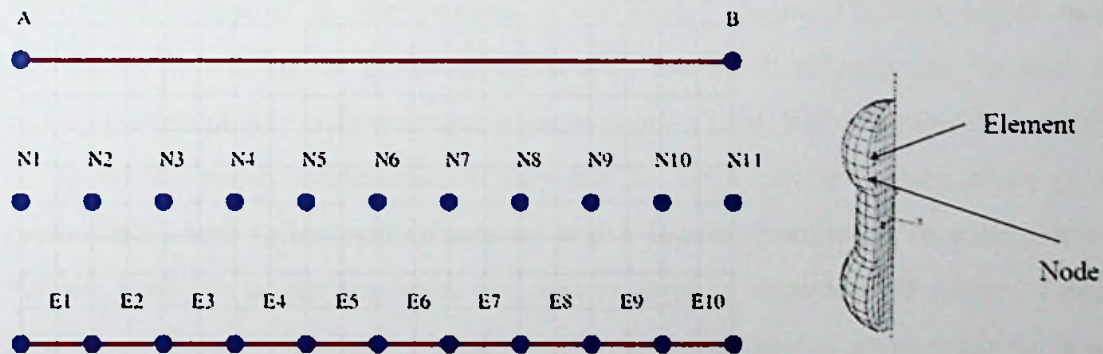


Figure 45 Nodes and Elements for FEM
(54)

The finite element mesh subdivides the computer aided design (CAD) model into smaller domains called elements where every element is solved with a set of equations (55). The meshing will depend on the material properties; depend on the shape of the solid body and on the boundary conditions. Boundary conditions are defined as any prescribed quantities, such as prescribed displacements and prescribed tractions on the boundary. As an example, when a force is applied on solid object the

values of stress, strain and displacement are given as change of boundary conditions (56)

The displacement of elements is occurred because of an external force that acted on the solid body that caused deformation. Displacement of each element is approximated by an equation. Solving of these linear equations will provide the solutions. Hence analyzing and visualization of the results of these linear equations is called as FEA (57).

The use of FEA software begins with designing of a CAD model. The accuracy of the results obtained from any FEA model is directly related to the finite element mesh that is used (55). If the element is made smaller the mesh becomes more refined. In general, meshing starts with a very coarse mesh, as a rough verification and to check on the correctness of the applied loads and constraints (55). Coarse mesh requires less computational resources to solve, but, it provides an inaccurate solution. Mesh refinement is the process of resolving the model with successively finer and finer meshes. Upon getting at least three results it becomes evident that the results are becoming more and less variable (55).

Mesh refinement can be made in two ways; globally and locally. Local mesh refinement is applied at one location in the model (figure 47), and global mesh refinement is used in the entire model space (55). Mesh refining can be done by reducing element size or by increasing element order (55). Reducing the element size is the easiest mesh refinement strategy due to simplicity. However, there is no preferential mesh refinement in regions and a locally finer mesh may be needed. Further, heavy computer resources and time is required to perform this type of mesh refinement strategy. Increasing element order is advantageous as re-meshing is not needed and the same mesh can be reused. The elements will have different arrangements and orders. Re-meshing is time consuming for complex 3D geometries or sometimes cannot be altered as they come from an external source. The disadvantage to this technique is that the computational requirements increase faster than with the reducing element size technique. Solutions from the two techniques used for a loaded plate with a hole are given in figure 48 and figure 49.

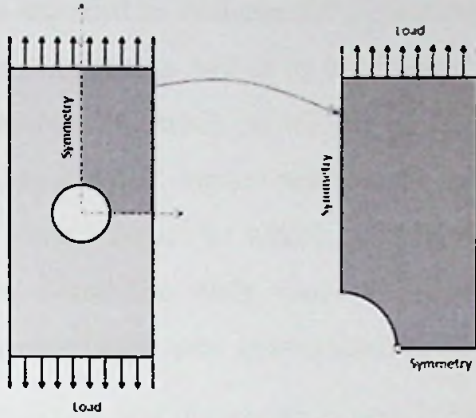


Figure 46 Local mesh refinement
(55)

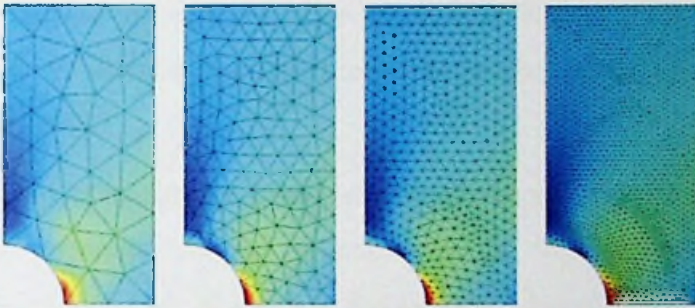


Figure 47 The stresses in a plate with a hole, solved with different element sizes
(55)

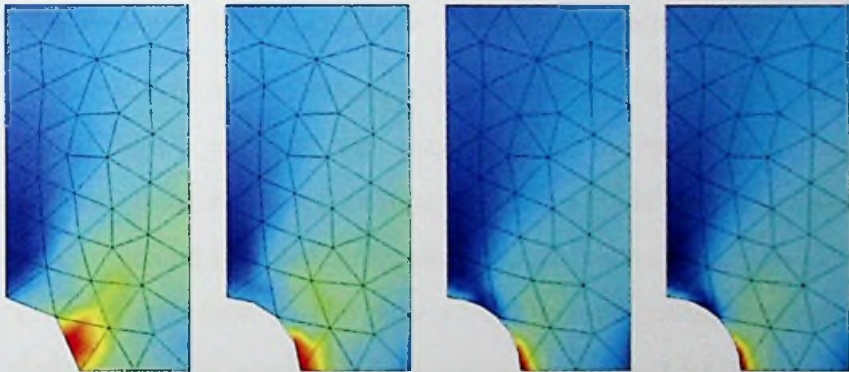


Figure 48 The same finite element mesh, but solved with different element order
(55)



2.9. Use of FEA in Automobile Industry

The wheel impact test is intended to evaluate the impact performance of wheel. The test is conducted by allowing letting striker to be dropped from a specified height above the tire wheel assembly. The study carried out by Chia-Lung Chang and Shao-Huei Yang was on simulating wheel impact test. Plastic concept of ductile fracture was used to predict the impact failure of wheel. ABAQUS Finite element software was used to perform the simulation study. Once the results were obtained it was revealed that results from simulation were almost same as of physical impact test (58).

A study on optimizing thickness and improving critical zone on a rim was conducted by H. Akbulut. A quadrant of the rim was utilized due to its symmetric shape in order to optimize the simulation process. The theoretical results were compared with experimental ones. It showed that the theoretical results are in agreement with the experimental ones. (59)

A three-dimensional re-meshing scheme was implemented by J. H. Yoon and D. Y. Yang for use of a modular concept proposed for the finite element analysis of a complicated forging process. A process forging of a bevel gear was taken in to simulation by using finite element analysis. The computational results are compared with experimental data in order to check the validity of the simulation (60)

A method for evaluation of the fatigue life of aluminum wheels was developed by Wang L. The ABAQUS software was used to build the static load finite element model of aluminum wheels. The equivalent stress amplitude was calculated based on the nominal stress method by considering the effects of mean load, size, fatigue notch, surface finish and scatter factors. The results from the aluminum wheel rotary fatigue bench test showed that the baseline wheel failed the test and its crack initiation was around the hub bolt hole area that agreed well with the simulation. Using the method proposed the wheel life cycle was improved to over 1.0×10^5 (61).

Dynamic cornering fatigue test on wheel was simulated and tested successfully. Before going it into production using ANSYS 11.0 environment by M. Lalit and Kachare, They developed a parametric representation for the forces and showed analytically and through simulation that the force distribution successfully simulated the loading conditions as required by standards for cars and for truck/bus wheel rims (62).

Deformation behavior of the car wheel rim when subjected to different loading conditions using Finite element analysis (FEA) was studied by M.Sabri. The car wheel rims which were made of steel and alloy have been modeled using Solidwork. From the results of modeling and simulation, it was found that the steel wheel rim produced high stress and deformed twice when compared with the alloy wheel rim. This concluded that due to high rigidity the steel wheel rim could absorb additional loads which could be avoided with more flexible structure. That means the steel rim needed to be only moderately rigid to withstand the uneven road condition and potholes (63).

An analysis on rolling contact fatigue of urban train wheel using FEM analysis was conducted by T.Y. Kim. FEM analysis was performed using ABACUS and 3D modeling was done using Pro E cad software for a rail and a wheel. During this analysis the slope of the rail, nonlinear isotropic and kinematic hardening behavior of the rail and the wheel were also taken in to consideration (64).

3. Material and Methodology

The following areas were intended to be covered under this section. This section includes selection of material, design of the product for load bearing and structural stability, manufacturing of the mold, material testing, manufacturing process and manufacturing machinery selection and physical product testing

3.1. Selection of the suitable material for manufacture of rim

The experiments were conducted with the commonly available materials in the local market to build the prototype sample. The materials are Nylon 6, Nylon 6 with 30% Short glass fibers, Nylon 6 with 50% long glass fibers and Nylon 6 with 50% short glass fibers

3.1.1. Nylon 6

Nylon 6 was of Ultramid 8202 injection molding grade supplied by BASF. It was a low viscosity, general purpose Nylon 6, injection molding homopolymer exhibiting excellent melt fluidity for filling thin sections. It combined good strength, stiffness and toughness as well as excellent heat, chemical and abrasion resistance. Major properties are given in table 5. Detailed Specification for the used plastic is given in Appendix 1.

Table 5 Material Properties of Nylon 6

	Tested at Temperature	Dry	Conditioned (Appendix 5)
Tensile strength MPa	23 °C	79	60
Elongation at break,%	23 °C	4	16
Rockwell Hardness, R scale	23 °C	119	
Flexural modulus, MPa		2830	740
heat deflection at 1.8MPa,°C		65	

3.1.2. Nylon 6 with 50% long glass fibers

Nylon 6 with 50% long glass fibers was of “BASF Ultramid® B3WG10 LF” grade. According to the BASF specification sheet Nylon 6 with 50% long glass fibers is reinforced, stabilized and high heat aging resistant. Detailed Specification sheet is given in Appendix 2. This new Nylon fiber system provides improved fiber bonding with plastics, which results in a more stable fiber skeleton structure. Due to its high weld line strength and creep resistance, Ultramid Structure LF (long fibers) can

withstand extreme stress. (65) Article, The effect of electron beam irradiation on properties of virgin and glass fiber-reinforced Nylon 6 has elaborated about the effects of presence of glass fiber with Nylon.

3.1.3. Nylon 6 with 30% short glass fibers

Durethan BKV 30 H2.0 901510 is the trade name for used Nylon 6 with 30% short glass fibers. This plastic was designed to withhold service temp of 200 °C for longer periods. The other most significant feature is that the tensile strength reduced only by 5% after service of 2,000 hours of hot-air storage at 200 °C. Two sizes of glass fibers of long and short structures are given in figure 50. (66)



Figure 49 Nylon short glass fiber vs. long glass fibers (66)

3.1.4. Nylon 6 with 50% short fibers

KOPA KN133G50 is also another brand of Nylon 6 with 50% short glass fibers that also was used for the test. Data specifications sheet is attached in the Appendix 3 It was supplied from Korea KOLON, Korea. Properties of this grade were similar to those of Durethan BKV 30 H2.0 901510. However strength and heat deflection temperature was higher.

3.2. Characterization of plastics

Specific gravity and melting temperature of all selected materials were studied and then were fed to the software in order to start the designing stage.

3.2.1. Specific Gravity

The specific gravity of plastics was measured using “SG meter SKZ300 A- meter for solids”. Test procedure was done according to ISO 1183-1 Standards “Plastics Methods for determining the density of non-cellular plastics, method A Immersion method”. Solid sample of plastic of about 5gr. was prepared by compression molding and tested.

3.2.2. Melting Temperature

Melting temperature of plastics was determined with OptiMelt MPA100 Automated. This apparatus provided a fast and accurate means of automatically determining the melting points and melting ranges of chemical substances with the help of microprocessor - controlled temperature ramping and a built-in digital camera

The melting temperature was measured according to ISO 3146:2000 (EN) Standards “Plastics- Determination of melting behavior (melting temperature or melting range) of semi-crystalline polymers by capillary tube and polarizing-microscope methods” Method A: Capillary tube.

As per this method the melting point was measured by inserting a small piece of material in to the apparatus capillary. Samples were viewed on the front panel through a removable magnification lens. This method is based on the changes in the shape of the plastic sample and it is applicable to all semi-crystalline polymers and their compounds.

3.3. Designing Tools and Product Design

The procedure for designing the plastic rim was conducted in 4 stages. The designing stages were described below:

- i. Initial design phase was started from a selecting a similar product traditional steel rim available at market.
- ii. Re-designing of the product according to material specification for load bearing and structural capability as per customer requirements
- iii. The product was FE Modeled and simulated to identify and eliminate stressed areas which could be potential for product failure.
- iv. Optimization of the designed structure for Injection molding

The designing procedure included number of stages in where structure of steel rim was continuously changed such a way to bring stresses and deflection under specified loading conditions down to the acceptable level. Other words this methodology was similar to prototyping methodology in where finalized result was archived upon successful completion of the designing stages. The design process comprised many repetitions made many times, so as the software received sufficient information to process and optimize structure with minimum changes to main design. The most suitable software for this task was identified as Solid work Simulation Package (45).

Solidwork Plastics software was used to identify and correct the possibly occurring injection molding defects. Those defects also required corrections through modifications of the product design and the injection mold.

After obtaining the required product through optimizing and developing the basic design, the designed product drawings were prepared and given to a local manufacturer to start manufacture of the required tooling. The required tooling was of low cost injection mold for making the prototype samples.

Finite element analysis (FEA) was carried out to evaluate the behavior of the concept models as per the Static loading conditions. Difficulties were associated with uncertainties in defining the geometry, material and loads. Restraints of FE Modeling and Simulation Process included,

- i. Geometry creation as CAD model
- ii. Defining material properties
- iii. Defining boundary conditions (Loads and Restraints)
- iv. Meshing

In another word design stage process comprised: preparation of CAD drawings, development of FEA model, analysis of the results (figure 51) (34).

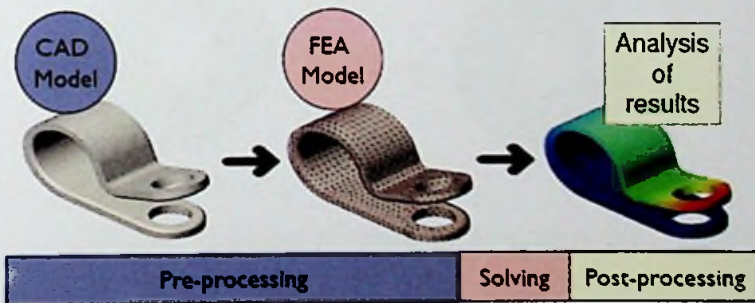


Figure 50 FEM stages

3.3.1. Design of Rim

Procedure started from the selection of the reference rim sample. For this purpose a standard steel rim was selected. As a next step 3D Model of the Steel Rim was created and simulated. During simulation rim structure was loaded with a specified force so as stress level and deflection were recorded.

Then the steel rim structure was changed for plastic one and 3D plastic Model was simulated. After identification of the weak points, the model was re-designed in order

to reinforce weak areas. This procedure was repeated until issue with earlier designed model were solved and stress level together with deflection came down to the acceptable level.

3.3.2. Stress vs. Contact Angle

To check effect of the load bearing surface on the stresses in the rim structure, the sector contact angle was changed from 10° to 150° . Simulation was done for 5° , 50° , 100° and 150° angle of contact area. As it could be seen from the results displayed on figure 52 and on the graph in figure 53, the load concentrated in the smaller area caused much higher stresses in the structure and there was significant drop in the stress when contact angle increased from 10° to 50° . From these results the load on the wheels was applied within 10° contact angle area for all simulation experiments for safety (67).

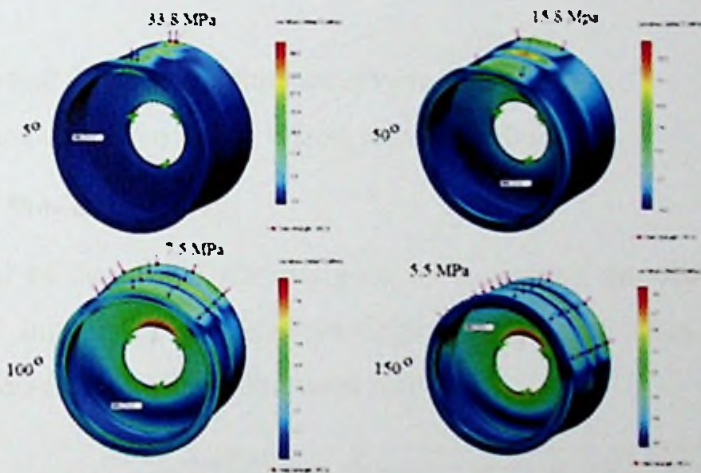


Figure 51 Effect of stress vs. contact angle

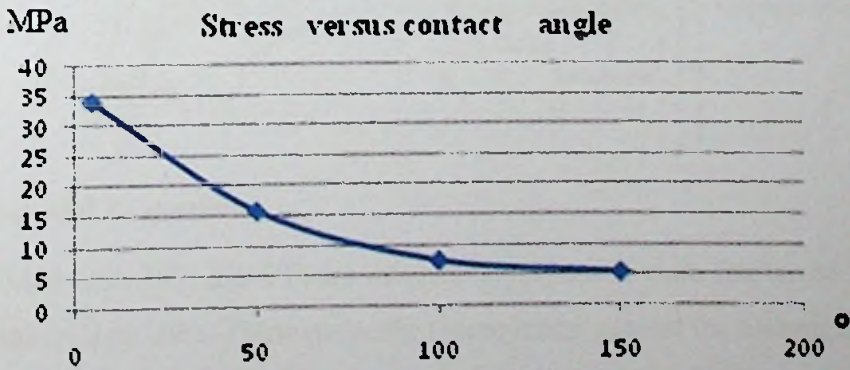


Figure 52 Effect of applied Stress Vs contact angle

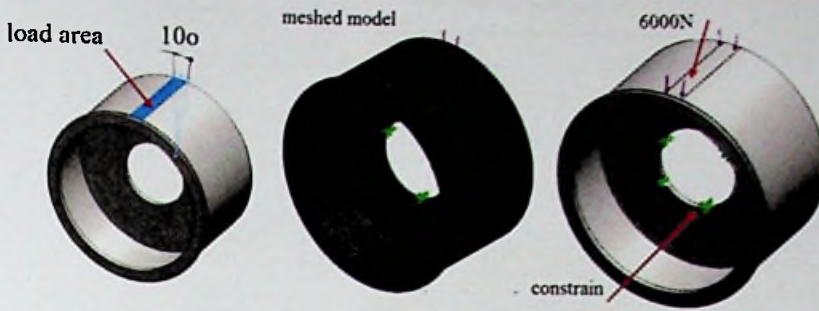


Figure 53 Application of force on the steel rim of FEM model

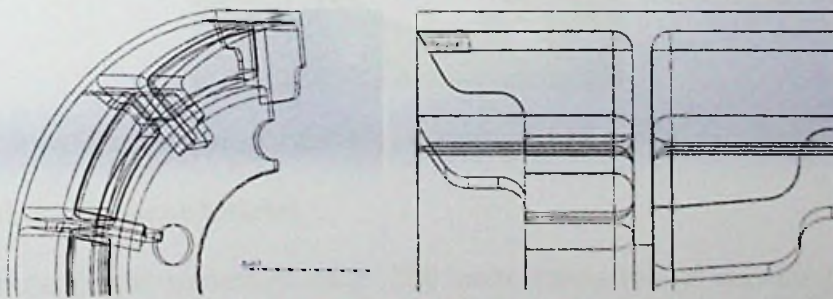
3.4. FEM Modeling

The following steps were followed to complete the FEM

- 3D CAD Model was created using Solid work software.
- Then material properties of Nylon 6 were included to the Solidwork data base. The material properties were obtained from the Technical data sheet of plastics
- Then external forces and fixture areas were identified.
- Contact angle of force and its effects were identified.

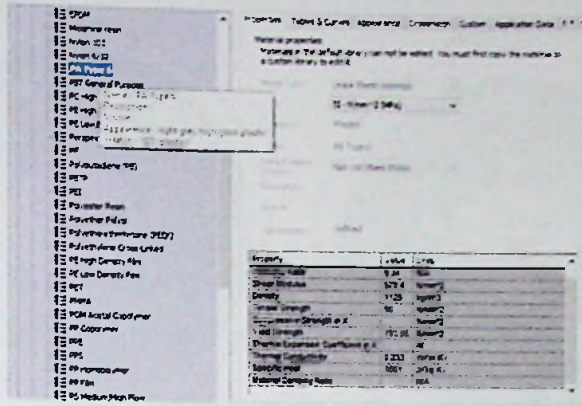
3.4.1. 3D CAD Model designing

A 3D cad model of the plastic was designed by measuring the dimensions of the reference sample. Initially 2D projected drawings were designed using Auto CAD and then 3D model was created using Solid word software.



3.4.2. Material Properties

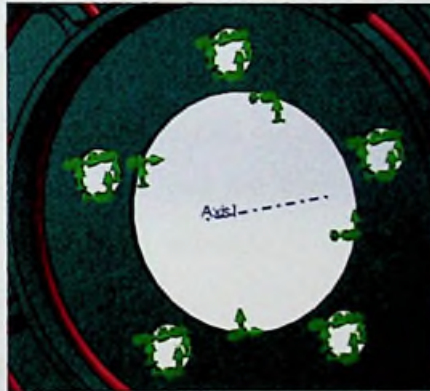
Nylon 6 filled with 30% glass fibers material's properties were fed to the Solid work inbuilt material data base. These properties were taken against the technical data sheet provided by the supplier. This data was expected to be used in CAD analysis.



3.4.3. Identification of Fixtures and external forces

Bolt and hub areas were the places from which the wheel was affixed. These were the areas where wheel came into touch with the vehicle assembly. Since there places were affixed they were marked as fixtures on simulation study.

According to solid work web page, Fixtures prescribed zero or non-zero displacements on vertices, edges, or faces for use with static, frequency, buckling, dynamic and nonlinear studies.



In green color the fixture surfaces and edges were marked for the selected rim design.

3.4.4. Mesh Refinement Metrics

The selected mesh was applied globally. The main reason behind was the position of the bolt holes. Due to the position of the bolts it was not possible to obtain the symmetry and since from the course Mesh applied globally showed fast stress spreading. (68)

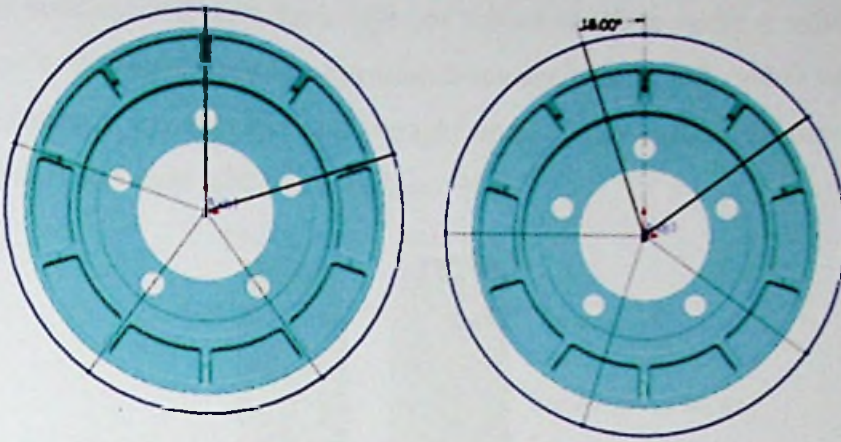


Figure 54 Difficulty of identifying symmetry for repetition

Mesh Refinement Techniques

For reducing the elements size the Mesh Refinement Techniques was used due to its simplicity in simulation study. The main issue that was faced with the reduction of the element size was related to the increased computational time. Due to this reason the mesh size was started from 15mm and was reduced to 5mm gradually until the expected stress and displacement values achieved the minimal difference.

Adaptive mesh refinement

Adaptively mesh refinement was not carried out on the product meshing. Pinpointing the stress and displacement location was not carried out for this simulation study. However it would have been much accurate if the locally or globally mesh was adapted to pinpoint the error location.

3.5. Designing of Nylon Rim

Initially evaluation of the trolley's and container dolly's trailer wheel with the rim made of steel was done. CAD drawings of the steel rim were prepared and properties of steel were defined. Sector angle of contact surface (load bearing surface was accepted at the beginning as 10° , mesh sizes were taken as 5 mm, 6 mm, 8 mm and 10 mm, constrain for load was defined as 6000 N .The force applied to one wheel was specified by customer for trolley's and container dolly's trailer wheel. The rim was fixed on 5 bolt holes and axle holes

- i. The following changes were made with the steel rim design on order to convert it into plastic rim.
- ii. Most Outer Diameter was increased from 239 mm up to 290 mm. – This is done in order to minimize the weight of the rubber used for tire by 50% as this

rim was covered with thick layer of rubber block to make a solid tire. Hard base rubber layer used for transition from steel rim to soft rubber was removed and plastic rim diameter was brought up to radius equaled to rim radius plus thickness of base rubber layer (figure 56).

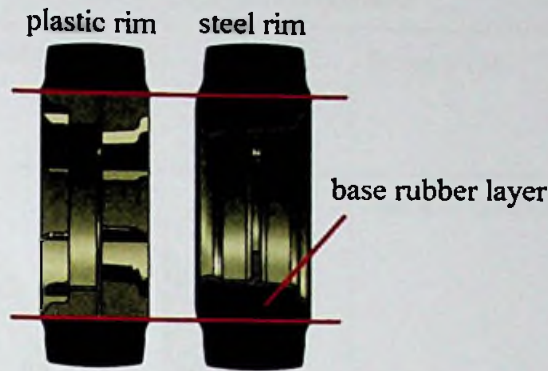


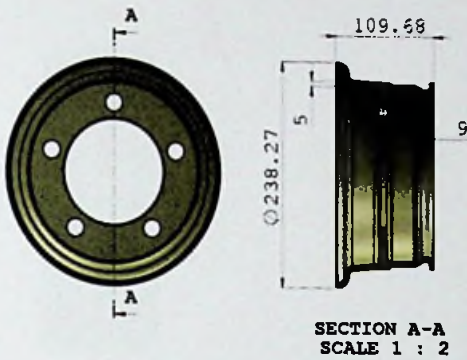
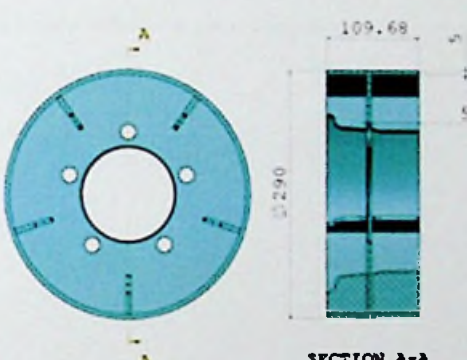
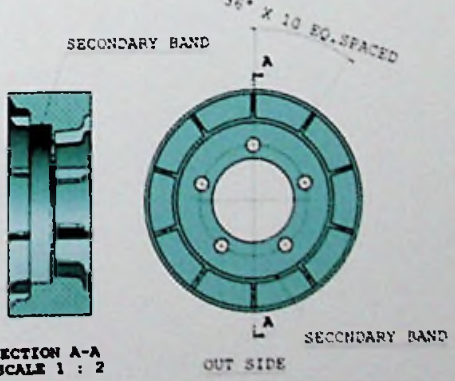
Figure 55 Nylon tire design vs standard tire

- iii. Width Remain Unchanged - If Rim width was wider then either it would be too wide and out of the limit of the vehicle or it would touch the vehicle chassis. If it was too thin then its load bearing ability would have been smaller and bots might not fit and tight properly.
- iv. Steel rim thickness of 5 mm on was maintained the same with plastic rim but the center plate thickness of 9 mm was changed to 5 mm. The reason for this was to keep uniform thickness throughout the product for trouble free injection molding related specifically to following:
 - To assure uniform stress concentration during the manufacturing stage of the plastic rim
 - To assure uniform time required for Solidification on all parts of plastic rim
 - Cost factor- Thick parts cost more in terms of material coast, machinery advancement cost and manufacturing lead time.

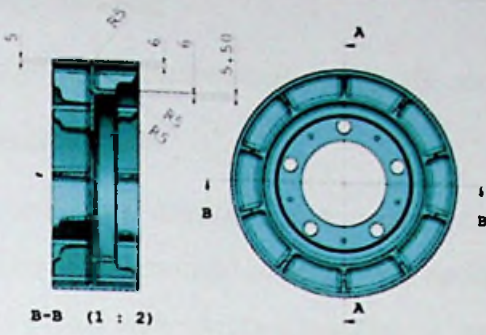
3.6. Comparison of rim models

The following models were designed and tested before manufacturing final prototype rim. Table number 6 contains the summary of designs.

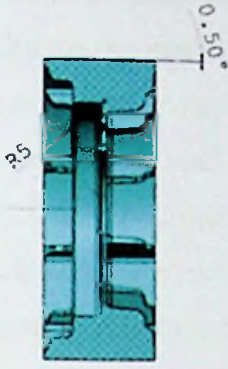
Table 6 Design comparison

Design Number	Product Technical Drawing	Description
01	 <p>SECTION A-A SCALE 1 : 2</p>	<p>Made of Q345B or similar material</p>
02	 <p>SECTION A-A SCALE 1 : 2</p>	<p>Has same width and outer diameter as Reference sample.</p> <p>Made of Nylon 6 30% Glass filled fibers</p> <p>Uniform thickness of 5mm is maintained on band and on 5 Numbers. of reinforcing ribs</p>
03	 <p>SECTION A-A SCALE 1 : 2</p> <p>OUT SIDE</p> <p>SECONDARY BAND</p> <p>36° X 10 EQ-SPACED</p>	<p>5mm Uniform with is maintained</p> <p>Number of Reinforcing ribs are increased from 5 to 10</p> <p>Secondary stress absorbing band is introduced.</p>

04



B-B (1 : 2)



A-A (1 : 2)

Main steel band is drafted for 0.5° easy removal from injection mould.

A steel plate insert is created and extruded boss is created to continue with plastic welding.

3.8. Injection Molding

Injection molding process was selected as the most efficient one.

3.8.1. Injection mold

Injection mold was designed and manufactured as per the developed product drawings. The injection mold structure was optimized during manufacture to avoid problem associated with injection molding of large complex parts. It was designed as a prototype mold to make 100 pieces. With intension of lowering the manufacturing time and reducing the manufacturing cost, it was decided to use a cheap less strength steel for prototyping, it may not be necessary to use a hardened tool steel. In most instances, pre-hardened steel is used to minimize cost and allow easy modification of the tool during the prototype stage. Therefore softer metals a pre-hardened tool steel P-20 was selected for mold manufacturing. This material also allowed molding of sufficient number of test pieces.

The single cavity injection mold contained two main parts categorized as ejector side and injector side. In addition to the main cavities said tie bars, ejector pins, venting holes, venting paths, cooling system and flow path were the major parts in where they worked simultaneously performing required functions to make a successful product.

Upon the completion of the injection mold, it was required to identify the suitable injection molding machine. Based on the material, product weight and clamping force the injection molding machine was selected



Figure 56 Injection mold under manufacturing

3.8.2. Injection Molding Machine

The used injection Molding machine was TOP 5 405 TN series of reciprocating screw type. It had shot capacity of 1430 g from Polystyrene. It used a hydraulic- toggle clamping mechanism to keep the mold closed and makes it open. The used machine was equipped with 4 place temperature controllers. Figure 58 and figure 59 show the machine barrel and machine respectively. Full machine specification is attached in Appendix 4.

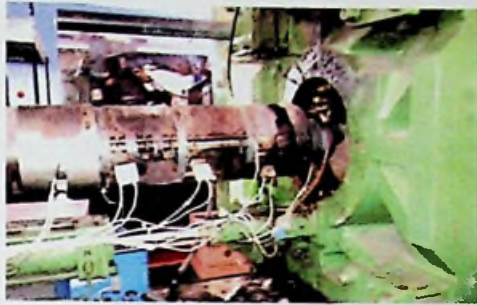


Figure 57 Barrel on injection molding machine



Figure 58 Injection molding machine

The injection molding machine had a heating capacity of 25 kW and a melt capacity of roughly of 2.1 kg from Polystyrene. A general purpose screw design (Fig.49) was used for injecting material to the injection mold while the nozzle was of an open type, heated and no shutoff valve was used. Schematic of the used nozzle is given in figure 60. The clamping force of the machine was 405 ton.

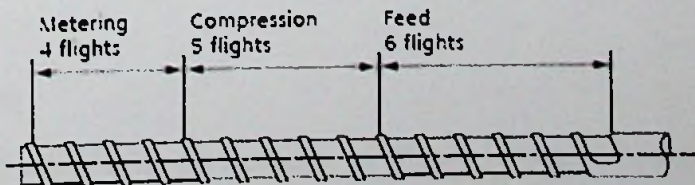


Figure 59 General purpose screw design
(43)

Using the Injection mold and the Injection molding machine, the product was manufactured. After manufacturing it was visually observed for identification of the injection molding defects and tested. Product was tested using tire testing bench. It was possible to measure withholding weight under static conditions. To perform endurance test the made rim was rubberized with rubber compounds to get a complete unitary wheel.

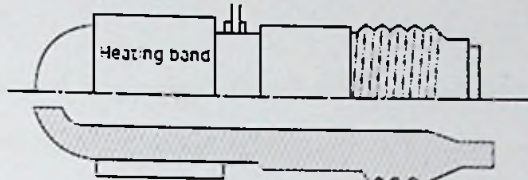


Figure 60 General purpose heating nozzle
(43)

3.8.3. Molding procedure

Following molding procedure was applied to the materials being processed.

Injection molding of Nylon 6

Since PA6 absorbs moisture readily, it has to be dried properly prior to molding. In spite of the material was supplied in watertight packaging, it was dried with hot air in the separate hopper at temperature of 70 °C for 4 hours. In case of processed delay, material was removed from the hopper and dried again.

It was recommended by plastic manufacturer to set cylinder temperatures ranging from 230-280 °C. A cylinder temperature profile was recommended to be set in such a way to keep the temperature of the feed section by 30-50 °C lower than the temperature of the nozzle. Improper cylinder temperatures could cause a variety of problems. Temperature was finally tuned during the experiment in order to avoid common injection molding problem.

Three separately controlled barrel heating zones were employed plus separate control for the nozzle zone.

Injection pressure

As injected rim comprised a large part of about 1.4 kg by weight the injection pressure was decided to be at the upper limit of 1,500 psi. Fine adjustment was also done during the experiment to avoid problem with filling the cavity, excessive shrinkage, voids, sinks, pigment dispersion, flashing. Injection time was 15 seconds.

Mold temperature

80 - 90 °C (176 - 194 °F). Mold temperature significantly influenced the crystalline level which in turn affected the mechanical properties. For structural part a high degree of crystallization was required and high mold temperatures of 60°C (176 - 194 °F) were set. High mold temperatures increased cooling time, but made it possible to increase the strength and hardness, cooling time was dependent on mold temperature and taken as 2 minutes.

Back pressure was selected in a range of 80.0-100 psi (gauge). The back pressure was used to remove air from the screw feed section.

Screw speed was ranging between 60 and 80 RPM.

3.8.4. Injection molding of Nylons filled with glass fibers

As all nylons tend to absorb moisture due to presence of amide groups it was necessary to pre-dry plastic prior to injection molding. It was done in a heated separated from injection molding machine hopper at temperature of 70°C during 3 hours.

As per data sheet provided by the manufacturers, injection molding or melt temperature for all nylons was around 280 °C, however a practical value needed to be obtained as depending on nozzle type severe drooling through the nozzle was observed at 215 °C, So temperature was reduced up to 200 °C. This resulted in turn in freezing the melt in the nozzle. Finally a melting temperature of 210 °C as the starting point was set for all used nylon plastics for TOP 5 general purpose injection molding machine.

The nozzle temperature in general depends on the design of the nozzle, the heater band placement, the temperature of the mold, the overall cycle and the type of nylon being processed. We have placed Nozzle temperature at 260 -265 °C during processing while the mold temperature was changed from 40 °C to 120 °C in order to select suitable one for best conditions such as high production rate and satisfactory of product appearance.

Injection pressure for the Nylon filled with glass fibers varied between the 35–140MPa. The pressure was balanced between necessity to fill the cavity completely and to proper pack the material inside cavity on one side and to avoid excessive flash

from the mold on another side. After several trials pressure was gradually adjusted and kept at 80MPa for a stable process.

A two stage injection pressurizing cycle was followed:

- i. Initially material was injected at high speed to fill the cavity
- ii. Holding under a reduced pressure to allow the gate to freeze and to prevent overstressing.

Then after injecting the product was left for cooling inside the mold for about one minute and then it was ejected from the mold.

3.8.5. Injection molding steps-start up.

- i. The Machine was left to heat up to the required temperature depending on the plastic material. This was done in such a way to keep starting barrel temperature by 30 °C below than that of melt temperature while the nozzle temperature was set by 10 °C above than melt temperature. Then the machine was left for 20 minutes until the heat was soaked.
- ii. It was assured that the nozzle didn't have any frozen material left.
- iii. The screw was jogged to make sure that the screw was moving and material inside the barrel was molten.
- iv. When the screw began to rotate, the hopper was opened and material was fed.. Then the material was pumped and load on screw motor was observed.
- v. In order to adjust the operating conditions until the material injected showed no indication of un-melted particles, back pressure was held up. Since backpressure was holdup the screw was rotating in forward position.
- vi. Several air shots with the stroke size and cycle anticipated for the molding operation were made and temperatures were checked. Cycle was set.
- vii. Then the injection Cylinder was brought forward and the molten plastic was injected into closed mold. The injection pressure was gradually increased until a perfect product was not obtained.

3.9. Tire Testing machine (Bench test)

The tire testing machine is used to verify the heat build-up and durability of solid and pneumatic rubber tires (figure 62). Also it was used to measure the rolling resistance, radial deflection, pressure in contact area and radial and axial run out of solid and pneumatic tires.

Plastic rim was tested under static and dynamic conditions. The tests were carried out to identify maximum compression force/pressure which rim was capable of withstand being stationary. The same experiment was simulated with FEA and obtained results were compared.



Figure 61 Tire testing bench

Tire testing machine was capable of testing two tires simultaneously as it was equipped with two drums. One drum was used for testing small diameter tires that was below 243.84 mm. large tires were categorized as tires with Diameter between 1219.2 mm and 1828.8 mm. The designed rim fell under small size tire category and was tested on the small side drum. Compression force applied on the small side was limited up to of 50 k N while on other side for large tires the force could be increased up to 300 k N. Both drums could be brought into rotation and speed was variable with the upper limit of 50 km per hour.

3.9.1. Static test

Plastic rim was fixed to axel and axel was fitted to the test bench. It was started with applying static force of 500 N and force was gradually increased up to 900 N. After the static force reached said value the rim was rotated once to identify deflection of the plastic structure. The applied force was gradually increased until break occurred. Breaking force and deflection at break were recorded.

3.9.2. Dynamic test

This test is commonly known as durability of endurance. To be capable to run several kilometers the plastic rim was covered with layer of solid rubber tire to get unitary complete wheel. Rubber was molded by traditional compression molded technology.

A rim with molded over it rubber tire was cooled to room temperature within 48 hours. *Rubberizing method was not described as this technology is a property of EuRetec Pvt. Ltd.* After molding the tire, two numbers of holes of 4 mm in diameter were drilled in the middle of the top and bottom of the tested sample in order to check the internal temperature of the rubber layer.

The rim with molded over it rubber tire was fixed on the test bench axle (figure 64).



Figure 62 Rubber molded tire

On the left: plastic rim, on the right: the same rim with molded rubber tire. Drum having smooth steel surface was brought into rotation at constant speed. Four load step were applied on the rim axel as per schedule given in table 7. Internal temperature of the rubber layer was measured.

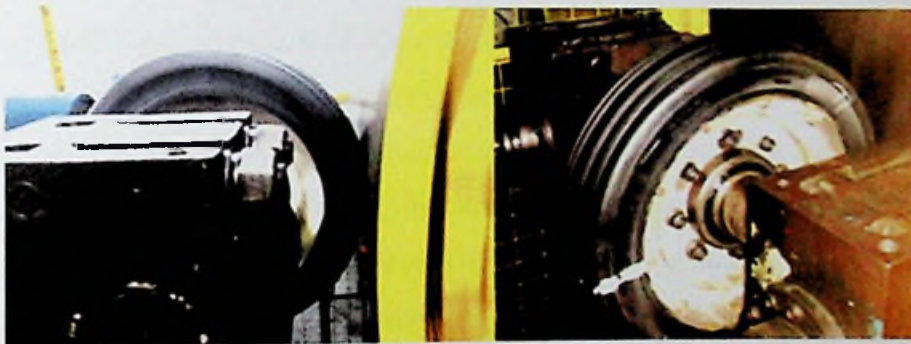


Figure 63 Dynamic testing in process

Table 7 Four load step on Tire Test Bench

Load level	100%	125%	150%	175%	200%
Running time	120 hours	96 hours	72 hours	48 hours	Until break

4. Results and Discussions

4.1. Properties of materials

Specific gravity and melting temperatures of the materials were measured and are given below in table 8. They are the inputs to the software. As glass fibers are highly resistant to high temperatures increase in glass fiber parentage in PA composition resulted in increase of melting point of composite. A study on effect of percentage of glass fibers in polyamide composite was conducted by M. Najafi, L. Nasri, R Kotek. (69) Their results have shown similar properties as of in this study.

Table 8 Specific gravity and melting temperature of materials

Number	Material	Specific gravity g/cm ³	Melting temperature °C
1	Nylon 6	1.14	215
2	Nylon 6 with 50% long glass fibers	1.43	223
3	Nylon 6 with 30% short glass fibers	1.35	210
4	Nylon 6 with 50% short glass fibers	1.45	220

4.2. Designing of Rim

This section covers evaluation of the critical loading conditions and various design scenarios relevant to the rim design, development of a sound finite element methodology (FEM) to carry out the stress analysis of the existing steel rim design, comparison and contrasting of simulation results of different test set-ups and thereby investigate FE model's stability, applying the simulation procedure to the conceptual design with plastic and understand the behavior of proposed models and identifying limits and approaches for optimization.

4.2.1. Evaluation and Simulation of steel rim

Stresses in the Steel rim and deformation as displacement were found and given below in table 9 and figure 65.

As it could be seen from the Table 8, there were no significant variations in the maximum stress when mesh size varied from 5mm to 10 mm. The point of maximum stress was observed in the bolt hole area and it was of 33.2 MPa a with maximum deflection of 0.019 mm for mesh size of 5 mm (figure 65).

Table 9 Steel rim stress & deformation

Study Number	Description	Applied static force (N)	Mesh size (mm)	Stress	Displacement (mm)
				(MPa)	
1	Steel Rim of Original Design	6.000	10	32	0.018
2		6.000	8	31.6	0.016
3		6.000	6	32.6	0.017
4		6.000	5	33.2	0.019

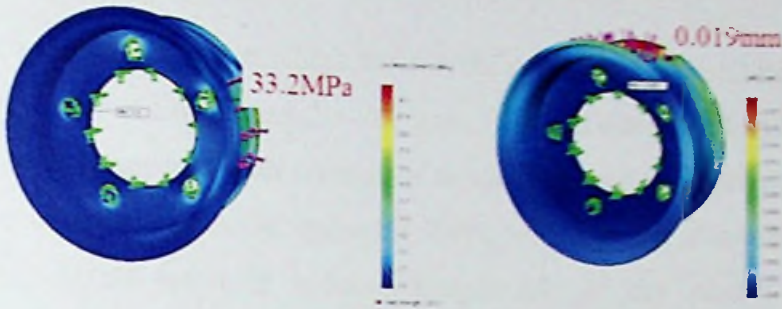
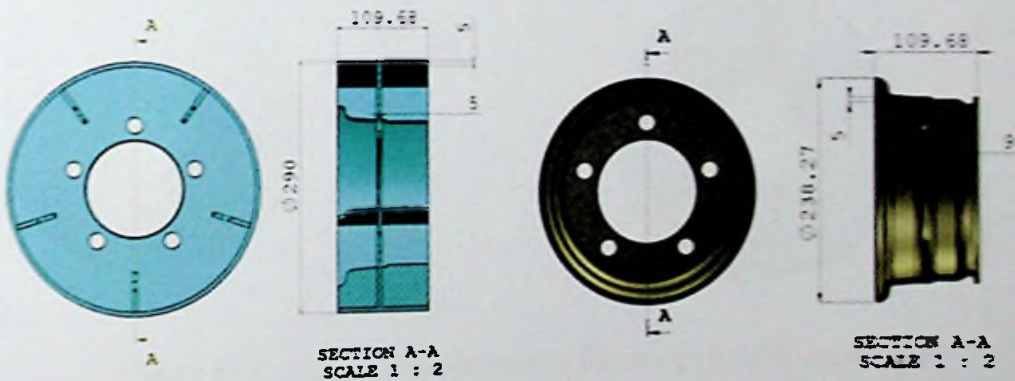


Figure 64 Simulated results of steel rim

4.2.2. Evaluation and Simulation of plastic rim

Design model no 01

Design number 01 as it was described above is given in figure 66



1
2
Figure 65 Standard steel rims (1)
Figure 66 Plastic rim design number 01 (2)

After designing the rim model number 01, the structure was simulated for static load and obtained results were presented in table 10

Table 10 Simulation results of the design model number 1

Study number	Description	Applied static force (N)	Mesh size (mm)	Max stress (MPa)	Max. displacement (mm)
4	Nylon rim, design number 01 (5 fixtures)	6,000	15	46.8	2.1
5		6,000	12	49.8	2.2
6		6,000	10	50.4	2.27
7		6,000	8	51.3	2.29

The Stress concentration was at a high level in the outer band areas. Also in addition to that the displacement was about 2.1- 2.3 mm. This was considered as high and not acceptable, when compared with simulation results obtained with reference sample. Compressive strain in the model exceeded 1.6%, which is not allowable for nylon plastics. This would result in reduced fatigue life of the plastic rim. Stress concentrated was about 50 MPa in average and this was near to the half of the Nylon 6 filled with glass fibers plastic. Yield strength of Nylon 6 reinforced with 30% short glass fibers is about 130 MPa. Due to these reasons the designed Model no1 was changed. A new model was proposed.

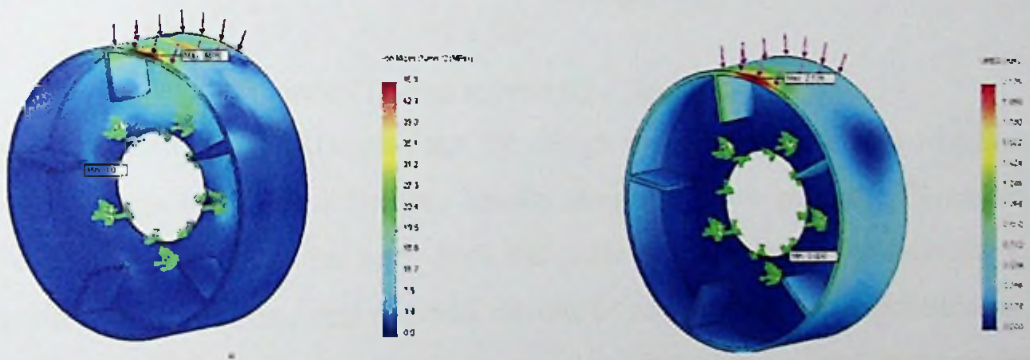


Figure 67 Design simulation results for design model number 01

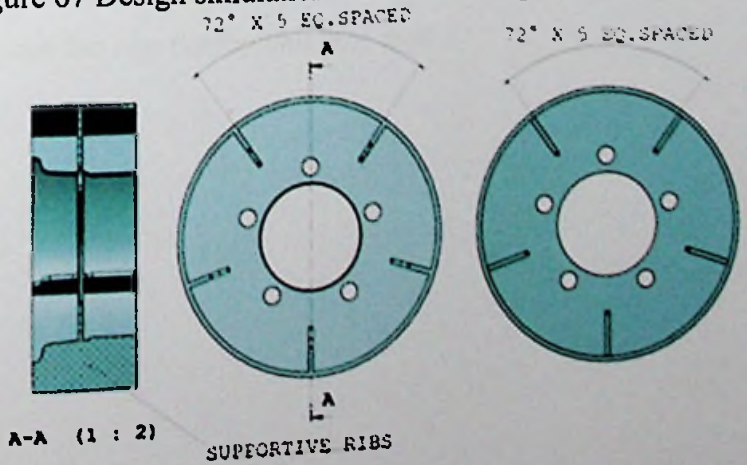


Figure 68 Design number 01- Detailed drawing

Design Model Number 02

The following changes were made in the design model number 01 to make design model no 2 in order to reduce stress level in the outer band area:

- i. The number of reinforcing ribs was increased from 5 to 10 and ribs were arranged keeping equally spaced distance corresponding to 36° angle.
- ii. A secondary band was introduced to the center (nave) ring on the side opposite to the vehicle axel. This secondary band was supposed to absorb stresses and reduce their level in the outer band area.

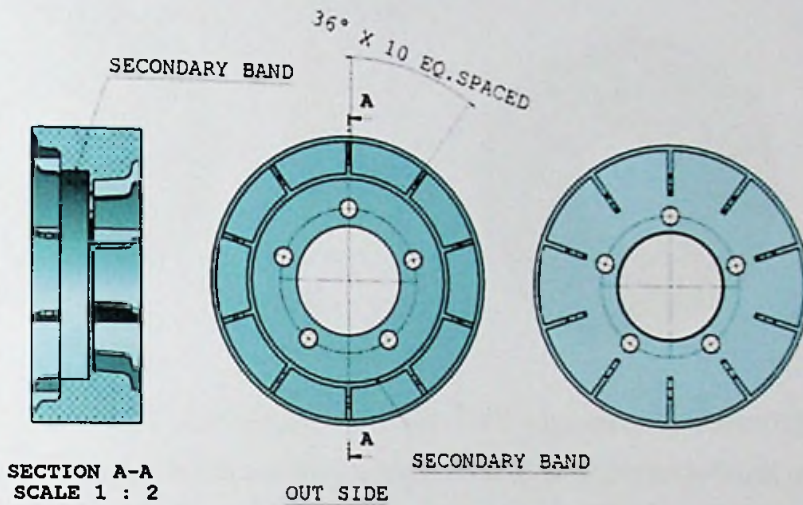


Figure 69 Design number 02 - Detailed drawing

After preparation of CAD drawings the design model number 2 was simulated to identify stress level and deflection. Results are given below in figure 71 and in the table 11. As it could be seen from the table 11 stresses were dropped down significantly when compared to model number 01 in where stresses were between 47-51 MPa in the outer band area, while in model number 02 outer band area was free of stresses and maximum stress level in a range of 23-26.8 MPa was observed in the nave ring between the ribs nearby bolt hole area.

Table 11 Simulation results of the design model number 02

Study number	Description	Applied static force (N)	Mesh size (mm)	Max. stress (MPa)	Max. displacement (mm)
8	Nylon rim, design model number 02	6,000	15	23.2	0.73
9		6,000	9	24.4	0.71
10		6,000	8	25.4	0.72
11		6,000	10	23.2	0.71
12		6,000	7	24.7	0.73
13		6,000	5	26.8	0.74

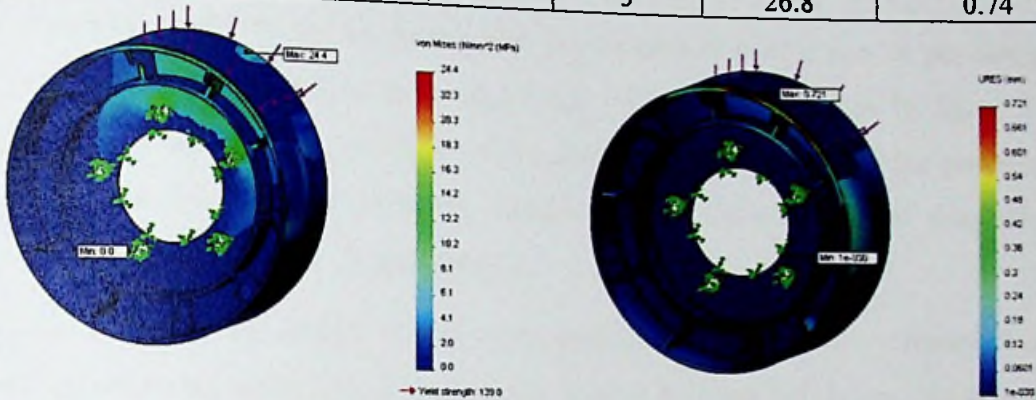


Figure 70 Design simulation results for design model number 02

When compared to the reference sample stress was at an acceptable level of 26.8 MPa keeping the safety factor more than 5 to the yield strength of Nylon .The displacement was also at an acceptable level between 0.7 mm.-1 mm. The design model number 02 required certain improvement in the bolt hole area and finalizing proposed structure to be injection molded. So this model needed to be optimized for conventional injection molding process. The standard procedure for designing the plastic parts was applied and a design model number 03 was developed based on the design model number 02.

Design Model number 03

The main design differences between the design model number 02 and design model number 03 are described as follows:

- i. As injection mold cavity was proposed to be very deep and equaled to half of the rim width (109 mm), ejecting such product from the deep cavity could not be free of trouble. For easy ejection of the rim from the mold cavity the draft angles of 0.5 o were introduced to the outer and inner band faces of the plastic rim. This resulted in reduction in the wall thickness of the rim at edges by score of millimeter and did not caused significant variation in wall thickness

uniformity for successful injection molding. Draft angles of 0.5° were also introduced to each rib on the outer band and secondary band.

- ii. Fillets were introduced at every place in where two surfaces intersected with each other and formed sharp angles, such as ribs intersected with central ring, the outer band and secondary band intersected with central ring. Fillets helped to avoid sharp edges usually leading to stress concentrated areas and all coming out these problems related to mold filling, ejecting and product quality.

3D drawings of the design model Number 03 comprised plastic rim as per design model number 02 with added draft angles and fillets as given below in figure 72. After completion of CAD drawings on the design model number 03, the proposed structure was simulated to evaluated stresses and deflection. Obtained simulation results were given in figure 71 and table 12.

After observation of results it was very clearly shown that the stresses were concentrated in the small area. This area was located between bolt holes. . In spite of the strength of the model was sufficient to withstand load, and displacement of 0.7 mm was at an acceptable level, this area was identified as a critical one in the design model number 03. There was only one solution to make this area safe, it was to reinforce that area with a steel plate. Steel plate was decided to fix to the central part of the plastic rim by staking assembling.

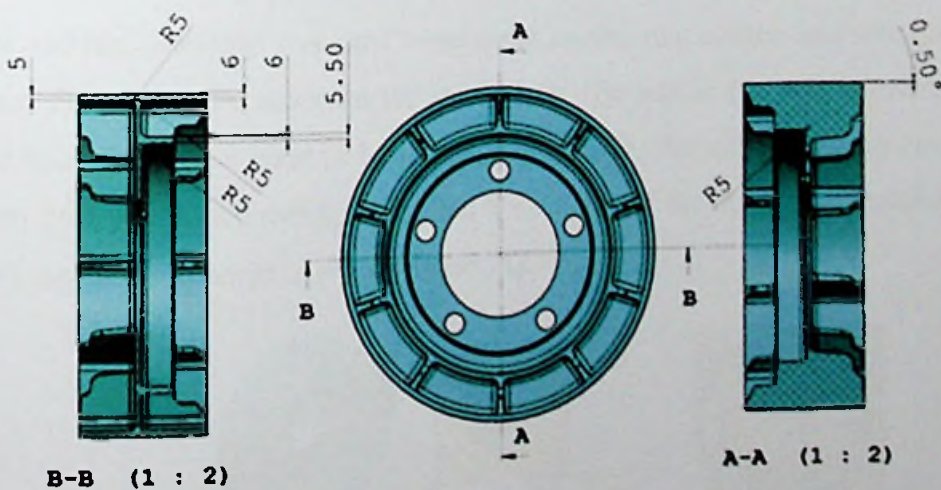


Figure 71 3D Drawing of design model number 03

Table 12 Simulation results of the design model Number 03

Study number	Description	Applied static force (N)	Mesh size (mm)	Max. stress (MPa)	Displacement (mm)	
				max	max	min
18	Optimized ribs, drafted and filleted joints. plates, ribs with draft of 0.5 °	6,000	15	54.6	0.787	0.0003

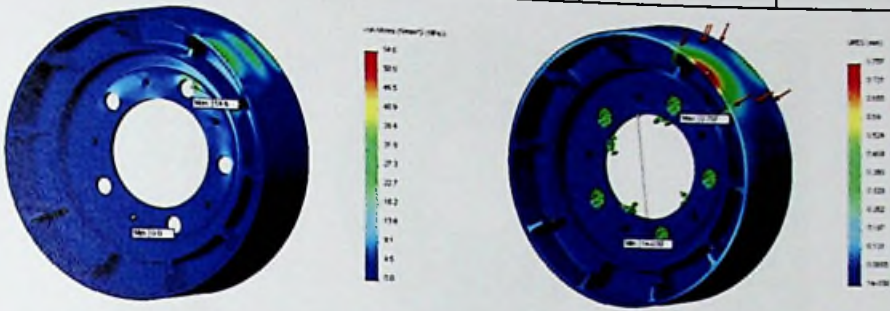


Figure 72 Design simulation results for design model number 03

Design model number 04

The design model number 03 was modified by addition of steel plate of 4 mm thick to central part of the rim on the bolt fixing side opposite to the vehicle axel. This steel plate helped to reduce excessive load on the rim and also ensured safety in case of excessive load was applied to the bolting screw when rim was fixed to the vehicle axel.

For staking assembly five pins were made on the rim surface and five holes of the same diameter were made on the steel plate. The plastic pin was protruded through the hole in the steel plate to be locked in place. The heated thermal tip contacted the top of the pin, which melted and filled the volume of the tip cavity to produce a head, locking the component in place (figure 74).

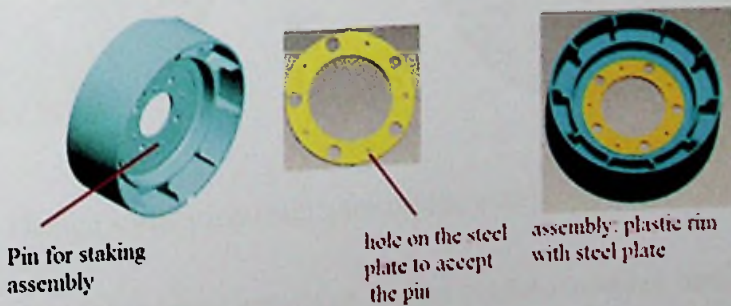


Figure 73 Steel ring holding mechanism

CAD drawings on the design model number 04 were prepared (figure 73) and model was simulated (figure 75 and table 13). As it was observed earlier the variation in mesh size had no significant effect on stresses and deflection in the rim, so use of mesh size of 15 mm for simulation of the design model number 03 and design model number 04 could save computation time and would not produce significant mistake.

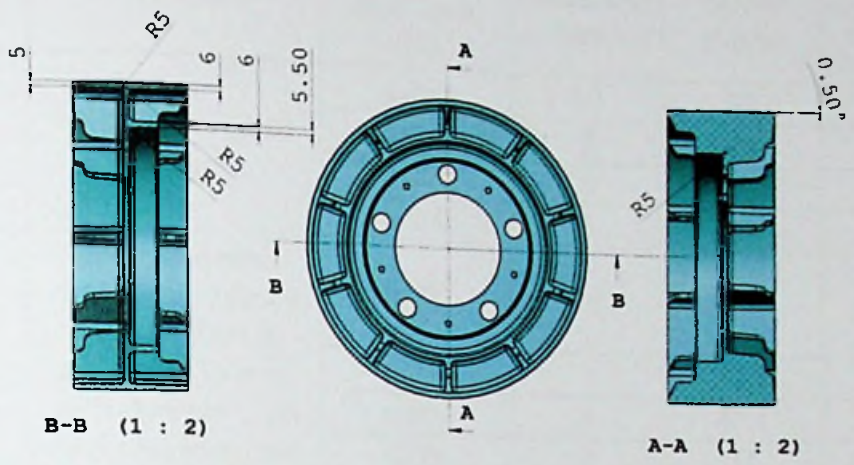


Figure 74 3D drawing of design model number 04
 Table 13 Simulation results of design model number 04

Study Number	Description	Applied static force (N)	Mesh size (mm)	Stress (MPa)	Displacement (mm)	
					max	min
17	Optimized ribs, drafted and filleted joints at 6000 N. mesh size 15 mm, with steel plate, rib drafted	6,000	15	27.6	0.832	0.0003

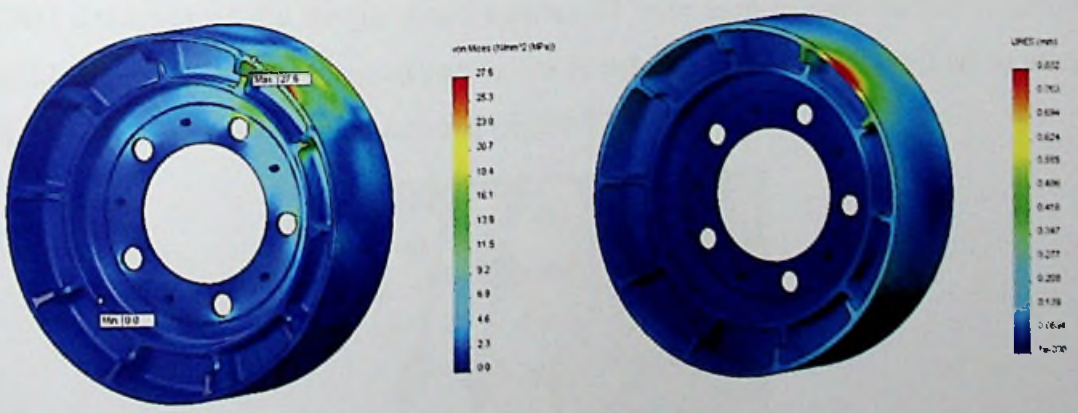


Figure 75 Design simulation results for design number 04 with 4 mm steel plate

Comparison of the simulation results of design model Number4 and reference steel rim model of the "original steel" design are given in table 14. It is clear that reinforced with steel plate plastic rim of the design model number 04 behaved in

manner similar to that of original steel rim .Finally the model number 04 and reference sample model were simulated applying smaller mesh sizes of 5 mm, 6mm,8mm and 10mm in order to check accuracy of the obtained final results

Table 14 Original steel rim vs. design model number 04

Study number	Description	Applied static force (N)	Mesh size (mm)	Stress (MPa)	max displacement (mm)
1	Steel rim, original design	6,000	10	32	0.018
2		6,000	8	28	0.014
4		6,000	6	32.6	0.018
5		6,000	5	28	0.014
17	optimized ribs, drafted and filleted joints at 6000 N. mesh size 15 mm, with steel plate, rib thickness increased	6,000	10	35.4	0.498
		6,000	8	37.5	0.5
		6,000	6	40.4	0.5
		6,000	5	41	0.51

As it could be seen from the table number13 effect of mesh size on displacement was negligibly small, while in case of stress for steel rim variance was 30 ± 2 MPa and in case of plastic rim variance was 38.2 ± 2.8 MPa

4.3. Production Stage

4.3.1. Injection molding

CAD drawings of the design model number 04 were used to manufacture injection mold. Mold with several central part inserts in order to fit the complete wheel to axels of various vehicles was manufactured (figure 77).



Figure 76 Injection mold with multiple inserts

4.3.2. Injection molding of Nylon 6 rim

Successful injection molding of Nylon 6 depended on mold design and material preparation. Additional Venting channels were placed to avoid burning marks. Diameter of the standard venting channels was also increased. Injected part was free of visually observed defects

Table 15 Modification of the injection mold done after trial with Nylon 6

Number	Modification	Location of modification in the mold	Reason for modification
1	Vent line number 1	Vent line was placed between runners	This helped to eliminate burning marks and to achieve proper weld.
2	Vent line number 2	Along elector pins	Total 6 pins were placed by 3 on both sides of the rim. Between two runner paths and on the last circle.

Introduction of additional vent lines made it possible to completely remove air from the mold and avoid plastic burning. Number black marks were observed. Mold temperature was set at 40°C that allowed fast cooling and short injection molding cycle of 55 seconds.

4.3.3. Long fibers filled PA 6

Injection molding process parameters were set as shown in table 16 to manufacture plastic rim with nylon 6 filled with 50 % long glass fibers. No flow to the mold was observed. Fibers were collected and stuck in the front chamber. Nozzle was completely blocked with fibers which also were severe damaged by screw. Conventional Injection molding machine and standard nozzle were not suitable of injection molding of plastic filled with high percentage of long glass fibers. To use injection molding machine for long glass fiber, the injection screw needs to be exchanged with the screw having smaller compression ratio of 2:1 and significantly reduced melting zone, keeping screw core as straight as possible. This is to be done to reduce unavoidable shear effects damaging fibers from snapping off and to avoid excessive wear of the injection screw. Nozzle also is required to have all mixing element removed and be fully open with large diameter and of short length.



Table 16 Injection molding process parameters LF/GF PA 6

Process parameters	Set up value
Mold temperature, °C	120
Melt temperature, °C	265
Volume flow rate, cm ³ /s	80
Holding pressure, bar	440
Back pressure	8
Screw rotation speed, rpm	60

4.3.4. Short fibers reinforced PA 6.

Nylon 6 with 30% short glass fiber and Nylon 6 with 50% short glass fibers were injection molded with conventional type injection molding machine. Injection molding of both materials was possible and rims were produced, however some problems were identified and related mainly to the injection mold design. Some adjustments were made to the existing injection mold structure and given in table 17. Those changes helped to avoid air entrapment in to the mold. This happened due to large volume of the injection mold cavity and number of venting channels was not sufficient to release this air from the mold during filling stage. Sprue and runner diameters were also increased to ensure fast flow to the mold cavity, as delay caused fibers separation when melt cooled and defects called whitening on the rim surface were observed.

Table 17 Adjustments to the injection mold structure

Number	Mold parts required modification	Modification	Reason
1	Sprue	the internal bore of the sprue bushing was tapered with diameters of and 10mm and polished	For fast flow and easy removing plastic from sprue
2	Mold runners	runners diameter was increased to 5 mm	For fast cavity filling
3	gate	width of the gate was increase up to 5 mm	For rapid filling and fast freezing

Another problem was associated with injected rim "whitening" (figure 78). It was observed that severances of whitening depended on mold temperature.

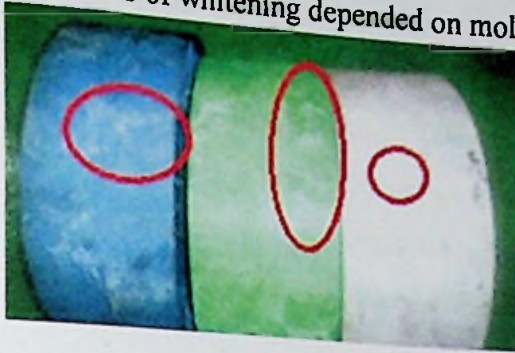


Figure 77 Whitening marks on the rim surface

When temperature was low in a range of 35 - 40°C whitened area was large. As temperature of the mold was increased from 40°C to 110°C cooling became slow, however whitening became not significant and almost disappeared. This could be explained as follows. Injected melt temperature was around 250°C. There was significant difference between cold mold and hot melt temperature. Fast cooling could facilitate absorption of glass fibers by metal. When mold temperature was increased cooling became slow and tendency to absorption of glass fibers by mold surface was reduced. Rim injected in to mold having temperature of 95 °C is given in figure 79.



Figure 78 Soft surface of the mold with increased injection molding temperature

4.3.5. Test results of molded rims under static and dynamic test conditions.

Molded rims were tested under static and dynamic conditions on tire testing bench.

Static test

Injection molded rims were tested by applying compression force on the rim until it was destroyed. Force versus deflection during static test was recorded and given in table 18. Minimum force per one wheel was specified by customer and it was at least

600 kg. The minimum safety factor was 2 and it was in case of nylon rim. According to basics of wheel dynamics the force on wheel at cornering may exceed load by 2 times. This means, that strength of all tested rims was sufficient for service under specified load. Rims made of glass fiber reinforced nylons were much stringer. 50% glass reinforced nylon rim was breaking into small pieces showing some brittleness. While 30% glass reinforced Nylon 6 exhibited some elasticity and break was not of brittle nature. Crack was observed on the inner surface of outer band (figure 80)



Figure 79 Band after static test result font
Table 18 Static test results

Number	Rim					
	Nylon 6		30% Glass reinforced PA6		50% Glass reinforced PA 6	
	Force, kg	Deflection, mm	Force, kg	Deflection, mm	Force, kg	Deflection, mm
1	800	5.6	800	4.4	800	2.7
2	1200	6.2	1200	4.8	1200	3.1
3	1700	7.0	1700	5.8	1700	3.7
4	2200	7.8	2200	6	2200	3.9
5	2600	8.5	2600	7	2600	4.7
6	3000	break	3000	8	3000	5.4
7			3500	10.4	3500	6
8			4000	12.7	4000	6.9
9			4500	14.1	4500	break
			4600	break		

The influence of weight percentages of glass fiber reinforcement on the strength of rim agreed well with studies conducted on investigation of tensile and impact properties of nylons filled with short glass fibers. (Experimental investigation on the

mechanical properties of glass fiber reinforced nylon D M Nuruzzaman¹, A K M Asif Iqbal, A N Oumer, N M Ismail and S Basri from Faculty of Manufacturing Engineering, University Malaysia Pahang, Malaysia Faculty of Mechanical Engineering, University Malaysia Pahang, Malaysia. iMEC-APCOMS 2015 IOP Publishing IOP Conf. Series: Materials Science and Engineering 114 (2016) 012118 doi:10.1088/1757-899X/114/1/012118

Pure nylon showed the lowest stiffness or tensile modulus as it could be seen from the table 17 and the nylon composites showed improvement in the tensile modulus with the increased content of glass fiber up to 30%-50%. This improvement in properties could be attributed to the properties of glass fibers. The elongation at break was remarkably high for pure nylon while it was low for nylon composites, particularly, it was very low for 30% and when weight percentage exceeded 30% composite material became brittle. Ploughing action of fibers at their high weight percentage in composite inclined fiber breakage and cohesive matrix fracture contributes to composites to fracture in brittle manner.

Dynamic test

To perform dynamic test rubber tire had to be molded to plastic rim. In case of nylon rim, it was not possible to fit rim to the rim supporting structure in the mold. Due to high amount of moisture absorbed, dimensions of the rim changed. As bolt holes area was affected, rim needed additional grinding. Additionally to that high deflection under applied load made this material not favorable as compared to glass reinforced nylons such type of problems was not experienced with glass reinforced nylon rims. Tires were molded and tested for durability. During dynamic test the load of 600 kg was applied continuously and speed was changed as per three steps given below:

Step -01: Running at 10 Km/h speed for 7 hours

Step -02: Running at 15 Km/h speed for 6 hours

Step -03: Running at 25 Km/h speed until brunt-out.

Temperature inside the tire was recorded (Fig.78) and shown in Table 18

Table 19 Step 1- speed 10 km/h

Time, minutes	Distance ,km	in tire temperature, °C
0	0	30
15	2.5	67
60	10	96
120	20	103
180	30	105
240	40	105
300	50	105
360	60	105
420	70	105

Table 20 Step2 speed 15 km/h

Time, minutes	Distance ,km	in tire temperature °C
480	85	125
540	100	128
600	115	129
660	130	129
720	145	130
780	160	132

Dynamic test Graph

Figure Number 81 shows the distance vs. increases in the temperature at different loads.

Test results Endurance and heat buildup



Figure 80 Dynamic test result

As temperature of the rubber tire achieved 200°C during Step 3 at 25 km/h , softening point of nylon, the strength of plastic rim was drastically dropped down , crack was propagating from the hottest place and this crack destroyed rim. Test was stopped .This temperature was damaging for the structural stability. To avoid temperature increase during tire running, the plastic rim could be recommended for use only with manually driven vehicle or slow running vehicle in where speed does not exceed 5-10 km/ hour.



Figure 81 Destroyed wheel (destructive test)

5. Conclusion

- i. Plastic rim structure capable to withstand load of 6000 N at a maximum speed of 15 km per hour was designed using Solid work software.
- ii. For the tested plastics materials the preference was given to 30% short glass fibers filled Nylon 6 due to its high strength, temperature resistance and dimensional stability came through its low susceptibility to moisture absorption. In spite of the same tensile strength 50% short glass fiber filled Nylon 6 was not recommended for rim fabrication as its brittle nature resulted in breaking the structural integrity when impact occurred
- iii. As per selected material (Nylon30% filled with glass fiber for injection molding grade) a prototype Injection mold for about 100 PCS was designed, fabricated using mild steel P-20 and modified further for better ventilation to eliminate trapped air. The selection of conventional type injection molding machine was based on machines shot capacity.
- iv. The Solid work could be successfully used for designing and optimizing plastic product structure. Upon data collected with the help of software the product was successfully designed, manufactured and tested physically on a tire testing drum. Results performed with plastic rim showed that destructive load was between 3.000 t and 4.600 t that corresponded to safety factor of 5-7 in case of 6000N force applied. Hence the physically obtained results were similar to those derived from data generated with the help of Solid work .It could be concluded that software aided design and provided accurate results.

6. Future recommendation

As for further improvement it would be of practical use to develop cool running rubber compound that could not result in significant increase in tire temperature while moving at speed exceeding limit specified for solid tire. On the other side development of temperature resistance nylon plastic based compound will help to increase load bearing capability of plastic rim under elevated temperature. Considering both of the above it would be possible to design plastic rims at affordable cost for pneumatic tires to be used for highway vehicle, as at the moment it is implemented only on high standard and expensive vehicles as an option. The main issue faced of this type rim compared to steel rim, is that Rim behaves in a brittle manner and becomes unusable after a heavy impact at a very high speed. In this situation the steel rim only deforms. The main disadvantage of plastic rim when compared to steel one is low resistance to an accidental impact. However it was proved that compared to steel rims, plastic rim has better longer life span as it does not get deformed after meeting a minor moderate power impact, while steel gets deformed and after deformation the steel rim needs to be replaced as it causes vibration. After minor impact of moderate power commonly occurred during service plastic rim does not deform and only has chips or and minor cracks on the surface which do obstacle performance.



Figure 82 Damaged steel rim Figure 83 Tire fitted to the dolly



Figure 84 Tire fitted to the dolly

References

1. Quadrennial technology review. *An assessment of energy technologies and research opportunities*. [Online] Department of Energy, Spetember 2015. [Cited: March 21, 2017.] <https://energy.gov/sites/prod/files/2017/03/f34/qtr-2015-chapter8.pdf>.
2. *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends*. United States Environmental Protect Agency. United States : United States Environmental Protect Agency, 2016.
3. *Plastics Today*. Average vehicle could incorporate 350 kg of plastics by 2020. *UBM advanced manufacturing*. [Online] UBM plc company, 2017. [Cited: February 08, 2017.] <https://www.plasticstoday.com/automotive-and-mobility/average-vehicle-could-incorporate-350-kg-plastics-2020/39227525825149>.
4. National Highway Traic Safety Administration . *Review and Analysis of Potential Safety Impacts of and Regulatory Barriers to Fuel Efficiency Technologies and Alternative Fuels In Medium- and Heavy-Duty Vehicles*. [Online] National Highway Traic Safety Administration , June 2015. [Cited: March 21, 2017.] <https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/812159-revsafetyimpactsregulatoryfueefficiencytechmdhd.pdf>.
5. Siemens Product Lifecycle Management Software Inc. *FEA / Finite Element Analysis*. [Online] Siemens Product Lifecycle Management Software Inc, January 2017. [Cited: March 25, 2017.] https://www.plm.automation.siemens.com/en_us/plm/fea.shtml.
6. Society of Automotive Engineers. *Plastics and Plastic Processing for the Automotive Engineer*. Pennsylvania : Society of Automotive Engineers, 1967, 2013.
7. C.P.Reghunadhan. *Chemistry and You*. [book auth.] NAIR. s.l. : Notion Press, 2017.
8. *Steel vs. Plastics: The Competition for Light-Vehicle Fuel Tanks*. Alvarado, Peter J. Michigan : s.n., 1996.
9. UL Global. *Polyamide (Nylon) Plastic*. [Online] January 06, 2017. [Cited: March 17, 2017.] <https://plastics.ulprospector.com/generics/22/polyamide-nylon>.

10. Y. Wang, C. Sun, L. Niu, L.Z. Wu, C.H. Tung, Y.Z.Chen, Q.Z. Yang. *Polymer Chemistry*. Beijing : s.n., 2017.
11. DuPont. Chemical formula of the PEEK. *What is PEEK*. [Online] DuPont, 2017. [Cited: March 11, 2017.] <http://www.dollfus-muller.com/en/FAQ-General/what-is-peek.html>.
12. Detectamet. *Detectable PEEK Product Overview*. [Online] 2016. [Cited: Januray 21, 2017.] <http://www.detectamet.com/detectable-peek.htm>.
13. *Design Guide for Bonding Plastics*. USA : The Loctit, 2011.
14. M. Ciobanu, L. Marin, V. Cozan, M. Bruma. *Aromatic polysulfones used in sensor applications*. Romania : Petru Poni” Institute of Macromolecular Chemistry, A, 2009.
15. Wartusch, Jhonan. *Makromolekulare Chemie Macromolecular Symposia*. [book auth.] Wartusch. *Makromolekulare Chemie Macromolecular Symposia*. Germany : Research Institute AEG Insulating Materials Goldsteinstrasse, 1993.
16. Polycarbonate PC. *Polymers*. [Online] British Plastics Federation , 2017. [Cited: March 23, 2017.] <http://www.bpf.co.uk/plastipedia/polymers/Polycarbonate.aspx>.
17. UL Global. *Acrylonitrile Butadiene Styrene (ABS) Plastic*. [Online] March 2017. [Cited: March 03, 2017.] <https://plastics.ulprospector.com/generics/1/acrylonitrile-butadiene-styrene-abs>.
18. *Polymers. Synthesis of Addition Polymers*. [Online] William Reusch, May 05, 2015. [Cited: March 12, 2017.] <https://www2.chemistry.msu.edu/faculty/reusch/virttxtjml/polymers.htm>.
19. *Reactive Flash Simulation of the Continuous Melt Transesterification Process of Polycarbonate*. Q. Jichen, X. Xiaoli , C. Xianwu, Q. Jinping. 01, Guangzhou : South China University of Technology, 2007, Vol. 15.
20. PubChem Compound Database. *PET*. [Online] National Center for Biotechnology Information, March 14, 2017. [Cited: March 17, 2017.] <https://pubchem.ncbi.nlm.nih.gov/compound/444075#section=Top>.
21. *Polyamides and Polyimides*. [book auth.] Mustafa Akay. *Introduction to Polymer Science and Technology*. 2012.

22. S.Baur, R.C. Allen and Ronald. Moisture Related Faliure. [book auth.] Shell Development Company. *Plastic Material*. 2002.
23. K.L. Pickeringa, M.G.A Efendyab, T.M. Lea. A review of recent developments in natural fibre composites and their mechanical performance. *Applied Science and Manufacturing*. [Online] September 09, 2015. [Cited: March 12, 2017.] <https://doi.org/10.1016/j.compositesa.2015.08.038>.
24. Sinotech, Inc. Injection Molded Parts. *Injection molding*. [Online] Sinotech, Inc, February 2017. [Cited: March 05, 2017.] <https://www.sinotech.com/resources/tutorials/injection-molded-parts/>.
25. SAGE Publications. Journal of Reinforced Plastics and Composites. *A Comparison of Transverse Properties of 50% Short and Long Glass Fiber Reinforced Nylon 6/6 Resin*. [Online] SAGE Publications, January 2017. [Cited: March 15, 2017.] <http://journals.sagepub.com/doi/abs/10.1177/073168449801701803>.
26. Fatigue Performance of an Injection-Molded Short E-Glass Fiber-Reinforced Polyamide 6,6. Effects of Orientation, Holes, and Weld Line. *POLYMER COMPOSITES*. [Online] University of Michigan-Dearborn, 2006. [Cited: March 05, 2017.] https://deepblue.lib.umich.edu/bitstream/handle/2027.42/50650/20182_ftp.pdf?sequence=1.
27. DePolo, S. Wade. *Dimensional Stability and Properties of Thermoplastics Reinforced with Particulate and Fiber Fillers*. Blacksburg : Wade S. DePolo, 2005.
28. INTRODUCING AMIDES. [Online] Jim Clark , February 2016. [Cited: January 19, 2017.] <http://www.chemguide.co.uk/organicprops/amides/background.html>.
29. Amilan nylon resin. *Technical information injection-molding before injection-molding a nylon resin*. [Online] Troy Industriese, February 2017. [Cited: March 12, 2017.] http://www.toray.jp/plastics/en/amilan/technical/tec_007.html.
30. AMILAN Nylon Resin. *Technical Information / Injection-molding / Before injection-molding a nylon resin*. [Online] TORAY Industriese, January 2017. http://www.toray.jp/plastics/en/amilan/technical/tec_007.html.

31. The Difference between Type 6,6 and Type 6 Nylon. [Online] NVISTA, October 12, 2013. [Cited: March 21, 2017.] http://antron.net/na/pdfs/literature/K02510_N66vsN6_Tech_Bulletin_06_18_13.pdf.
32. High Temperature Thermoplastics. [Online] Thought Co, January 12, 2017. [Cited: February 06, 2017.] <https://www.thoughtco.com/high-temperature-thermoplastics-820349>.
33. John Wiley & Sons, Inc. *Injection molding*. [Online] January 2017. [Cited: February 09, 2017.] <http://onlinelibrary.wiley.com/doi/10.1111/j.1541-4337.2010.00126.x/full>.
34. DuPont™ Zytel® HTN. *high performance polyamide Molding Guide*. USA : Du Pont, 2001.
35. ICO Products. Calculate plastic mold shrinkage. *Poymer knowledge base subjects*. [Online] ICO Products LLC, 2016. [Cited: March 15, 2017.] <https://icomold.com/knowledge-base/calculate-plastic-mold-shrinkage/>.
36. Greene, Professor Joseph. *Polymer Shrinkage*. [Power Point Slides] United Kigdom : s.n., 2000.
37. DuPont Engineering Polymers. *Properties of Glass-Reinforced Zytel Nylon*. USA : DuPont Engineering Polymers, 2002.
38. The Rodon Group. *Scary plastic part defects and how to avoid them*. [Online] 2017. [Cited: March 05, 2017.] <https://info.rodongroup.com/bid/99262/plastic-injection-molding-101-common-plastic-part-defects>.
39. BASF Corporation . *Design Solutions Guide*. Germany : BASF Corporation , 2007.
40. Texas plastic technologies. Brittleness. *Plastic trouble shooter*. [Online] Texas plastic technologies, August 2010. [Cited: March 21, 2017.] <http://www.plastictroubleshooter.com/ThePlasticTroubleshooter/brittleness.htm>.
41. Discoloration. *Plastic Trouble Shooter*. [Online] Texas Plastic Technologies, August 25, 2010. [Cited: March 10, 2017.] <http://www.plastictroubleshooter.com/ThePlasticTroubleshooter/discoloration.htm>.

42. Texas Plastic Technologies. Flow lines. *Plastic Trouble Shooter*. [Online] Texas Plastic Technologies, August 25, 2010. [Cited: March 25, 2017.] http://www.plastictroubleshooter.com/ThePlasticTroubleshooter/flow_lines.htm.
43. BASF Plastics . *Injection Moulding Processing Guide Ultramid Nylon*. Germany : BASF Plastics , 2016.
44. Wellman engineering resins division. *Wellman engineering resins design guide*. Johnsonville : Johnsonville, 2009.
45. DuPont Engineering Polymers. *Injection Molding Processing Guide*. s.l. : DuPont Engineering Polymers, Germany.
46. —. *General Design Principles for DuPont Engineering Polymers Design Guide—Module I*. Germany : DuPont Engineering Polymers, 2001.
47. SIMUL8 Corporation. Simul 8. *Discrete Event Simulation*. [Online] 2017. [Cited: February 05, 2017.] <https://www.simul8.com/discrete-event-simulation>.
48. SIMUL8 Corporation. Simul 8. *Discrete Event Simulation vs. Real Life Experimentation*. [Online] 2017. [Cited: February 05, 2017.] <https://www.simul8.com/discrete-event-simulation>.
49. *International Journal of Application or Innovation in Engineering & Management* . P. Meghashyam, S. Girivardhan Naidu, N. Sayed Baba. 8, India : Madanapalle Institute of Technology & Science, 2013, Vol. 2.
50. *Design and Analysis of Wheel Rim using CATIA & ANSY*. International Journal of Application or Innovation in Engineering & Management . 8, 2013, Vol. 2. ISSN 2319 .
51. American Chemistry Council. National Research Council Committee on Fuel Economy of Light - Duty Vehicles. [Online] [Cited: February 21, 2017.] <https://plastics-car.com/NHTSA-NRC-Meeting-on-Lightweighting>.
52. *Rim and tyre investigation for the in wheel motor of an electric vehicle using simulations*. Kulkarni and A Kapoor. Adelaide : 20th International Congress on Modelling and Simulation, 2013 .
53. materials. [book auth.] Jeong-Won Lee 1 and Tae-Il Seo 2 Gun-Hee Kim 1. *Durability Characteristics Analysis of Plastic Worm Wheel with Glass Fiber Reinforced Polyamide*. Korea : Korea Institute of Industrial Technology, 2013.

54. *Finite Element Analysis*. Qi, Dr. H.J. United Kingdom : s.n., 2006.
55. Comsol Inc. Finite Element Mesh Refinement. *The Mesh Refinement Process*. [Online] Comsol Inc, February 2017. [Cited: April 7, 2017.] <https://www.comsol.com/multiphysics/mesh-refinement>.
56. Burkardt, John. *Meshing for the Finite Element Method*. [Online] Florida State University, November 4, 2011. [Cited: March 12, 2017.] https://people.sc.fsu.edu/~jburkardt/classes/fem_2011/fem_meshing.pdf.
57. J.Burkardt. *Meshing for the Finite Element Method*. [Online] Florida State University, November 04, 2011. [Cited: March 12, 2017.] https://people.sc.fsu.edu/~jburkardt/classes/fem_2011/fem_meshing.pdf.
58. *Simulation of wheel impact test using finite element method*. C.L. Chang, S.H. Yang. Taiwan : National Yunlin University of Science and Technology, 2009.
59. *On optimization of a car rim using finite element method*. Akbulut, H. Turkey : Elsevier Science B.V., 2002.
60. *A three-dimensional rigid-plastic finite element analysis of bevel gear forging by using a remeshing technique*. D.Y Yang, J. H. Yoon. Seoul, Korea : Pergamon Press plc, 1989.
61. *Fatigue Life Analysis of Aluminum Wheels by Simulation of Rotary Fatigue Test*. L. Wang, Y. Chen, C.Wang, Q.Wang. China : Journal of Mechanical Engineering, 2010.
62. *Simulation of Dynamic Cornering Fatigue Test for Wheel Rims: A Parametric Force Representation Approach*. M. Lalit, N.R. Kachare. 2, India : CURIE Journal, July 2010, Vol. 3.
63. *Deformation Behaviour Analysis Of Car Wheel Rim Under Different Loading Using Finite Element Method*. M. Sabri, M. Rezal, A. Mu'az, K. Shahril, J.Ihsan. 3, Malaysia : International Journal of Engineering, 2015, Vol. 5.
64. *Three-dimensional elastic-plastic finite element analysis for wheel-rail rolling contact fatigue*. T.Y. Kim, H. Kim. 3, Korea : International Journal of Engineering and Technology, 2014, Vol. 6.

65. *The effect of electron beam irradiation on properties of virgin and glass fiber-reinforced polyamide 6*. M. Porubská, I. Janigová, K. Jomová, I. Chodák. Slovakia : s.n., 2014, Vol. 01.
66. Durethan BKV30H2.0 901510 Datasheet. *30% Glass Fiber Polyamide 6*. [Online] LANXESS , 2017. [Cited: March 06, 2017.] <https://plastics.ulprospector.com/datasheet/e53855/durethan-bkv30h20-901510>.
67. *3D contact patch measurement inside rolling tyres*. A. Glenn Guthrie, Theunis R. Botha, P. Schalk Els. South Africa : University of Pretoria, 2016.
68. Comsol Inc. Finite Element Mesh Refinement. *The Mesh Refinement Process*. [Online] Comsol Inc, February 2017. [Cited: April 7, 2017.] <https://www.comsol.com/multiphysics/mesh-refinement>.
69. *9 – High-performance nylon fibers*. M. Najafi, L. Nasri, R. Kotek. Switzerland : Woodhead Publishing Series , 2016.
70. *Fatigue Life Analysis of Aluminum Wheels by Simulation of Rotary Fatigue Test* . Wang. L, Chen. Y, Wang.C. s.l. : Journal of Mechanical Engineering, 2010.
71. *Deformation Behavior Analysis Of Car Wheel Rim Under Different Loading Using Finite Element Method*. M. Sabri, M. Rezal, A. Mu'az, K. Shahril, J.Ihsan. United Kingdom : International Journal of Engineering and Technology, 2015, Vol. 5.
72. *Computer Aided Design and Simulation of Radial Fatigue Test of Automobile Rim Using ANSYS*. 1, Nigeria : IOSR Journal of Mechanical and Civil Engineering, 2014, Vol. 11.
73. Gun-Hee Kim, Jeong-Won Lee , and Tae Il Seo. Durability Characteristics Analysis of Plastic Worm Wheel with Glass Fiber Reinforced Polyamides. *Design of Plastic Worm Wheel and Injection Mold Materials*. 2013.
74. Siemens Product Lifecycle Management Software Inc. *FEA / Finite Element Analysis*. [Online] Siemens , January 2017. [Cited: April 04, 2017.] https://www.plm.automation.siemens.com/en_us/plm/fea.shtml.
75. *Durability Characteristics Analysis of Plastic Worm Wheel with Glass Fiber Reinforced Polyamide*. Gun-Hee Kim, Jeong-Won Lee, Tae-Il Seo. Korea : Materials 2013, 2013, Vol. 6.
76. *Finite Element Analysis*. Qi, Dr. H. J. United Kingdom : MCEN 4173/5173, 2006.

77. *Three-dimensional elastic-plastic finite element analysis for wheel-rail rolling contact fatigue.* A.Y. Kim, H.K. Kim. 3, Korea : s.n., 2014, Vol. 6.

Appendix 1

BASF Novolen® 1100 N Polypropylene, Injection Molding Grade

Categories: Polymer; Thermoplastic; Polypropylene (PP); Polypropylene, Molded



Material Notes: Grade for injection molded parts. Also available as a special grade for fibers (short spinning) and cast film.



Data was collected by ISO methods and provided by BASF.

Key Words: PP

Vendors: No vendors are listed for this material. Please [click here](#) if you are a supplier and would like information on how to add your listing to this material.

Physical Properties	Metric	English	Comments
Density	0.910 g/cc	0.0329 lb/in ³	
Water Absorption	0.10 %	0.10 %	
Moisture Absorption at Equilibrium	0.10 %	0.10 %	
Linear Mold Shrinkage, Flow	0.013 cm/cm	0.013 in/in	
Melt Flow	16 g/10 min @ Load 2.16 kg Temperature 230 °C	16 g/10 min @ Load 4.76 lb. Temperature 446 °F	

Mechanical Properties	Metric	English	Comments
Tensile Strength, Yield	35.0 MPa	5080 psi	
Elongation at Break	>= 50 %	>= 50 %	
Elongation at Yield	10 %	10 %	
Tensile Modulus	1.55 GPa	225 ksi	
Charpy Impact: Unnotched	11.0 J/cm ²	52.4 ft-lb/in ²	
 Charpy Impact, Unnotched	1.50 J/cm ² @ Temperature -30.0 °C	7.14 ft-lb/in ² @ Temperature -22.0 °F	
Charpy Impact, Notched	0.300 J/cm ²	1.43 ft-lb/in ²	
 Charpy Impact, Notched	0.150 J/cm ² @ Temperature -30.0 °C	0.714 ft-lb/in ² @ Temperature -22.0 °F	
Tensile Creep Modulus, 1 hour	700 MPa	102000 psi	
Tensile Creep Modulus, 1000 hours	380 MPa	55100 psi	

Electrical Properties	Metric	English	Comments
Electrical Resistivity	>= 1.00e+15 ohm-cm	>= 1.00e+15 ohm-cm	
Surface Resistance	1.00e+14 ohm	1.00e+14 ohm	
Dielectric Constant 	2.3 @ Frequency 100 Hz	2.3 @ Frequency 100 Hz	
	2.3 @ Frequency 1e+8 Hz	2.3 @ Frequency 1e+8 Hz	
Dielectric Strength	140 kV/mm	3560 kV/in	
Dissipation Factor 	0.000070 @ Frequency 100 Hz	0.000070 @ Frequency 100 Hz	
	0.000020 @ Frequency 1e+8 Hz	0.000020 @ Frequency 1e+8 Hz	
Comparative Tracking Index	600 V	600 V	

Thermal Properties	Metric	English	Comments
CTE, linear, Parallel to Flow	135 µm/m-°C @ Temperature 20.0 °C	75.0 µin/in-°F @ Temperature 68.0 °F	
Melting Point	163 °C	325 °F	
Deflection Temperature at 0.46 MPa (66 psi)	85.0 °C	185 °F	
Deflection Temperature at	55.0 °C	131 °F	

1.8 MPa (264 psi)

Vicat Softening Point

Flammability, UL94

92.0 °C

198 °F

HB

HB

@Thickness 3.18 mm

@Thickness 0.125 in

Some of the values displayed above may have been converted from their original units and/or rounded in order to display the information in a consistent format. Users requiring more precise data for scientific or engineering calculations can click on the property value to see the original value as well as raw conversions to equivalent units. We advise that you only use the original value or one of its raw conversions in your calculations to minimize rounding error. We also ask that you refer to MatWeb's [terms of use](#) regarding this information. [Click here](#) to view all the property values for this datasheet as they were originally entered into MatWeb.



Appendix 2

Durethan BKV 30 H2.0 901510

PA 6, 30 % glass fibers, injection molding, heat-aging stabilized
 ISO Shortname: ISO 1874-PA 6, GHR, 14-090, GF30

Property	Test Condition	Unit	Standard	guide value	cond.
				d.a.m.	
Rheological properties					
C Molding shrinkage, parallel	60x60x2; 280 °C / MT 80 °C; 600 bar	%	ISO 294-4	0.3	
C Molding shrinkage, transverse	60x60x2; 280 °C / MT 80 °C; 600 bar	%	ISO 294-4	0.69	
Post- shrinkage, parallel	60x60x2; 120 °C; 4 h	%	ISO 294-4	0.06	
Post- shrinkage, transverse	60x60x2; 120 °C; 4 h	%	ISO 294-4	0.13	
Mechanical properties (23 °C/50 % r. h.)					
C Tensile modulus	1 mm/min	MPa	ISO 527-1,-2	9500	5800
C Tensile Stress at break	5 mm/min	MPa	ISO 527-1,-2	170	100
C Tensile Strain at break	5 mm/min	%	ISO 527-1,-2	3.5	6.0
C Tensile creep modulus	1 h	MPa	ISO 899-1		5100
C Tensile creep modulus	1000 h	MPa	ISO 899-1		4100
C Charpy impact strength	23 °C	kJ/m ²	ISO 179-1eU	75	90
C Charpy impact strength	-30 °C	kJ/m ²	ISO 179-1eU	65	60
C Charpy notched impact strength	23 °C	kJ/m ²	ISO 179-1eA	10	20
C Charpy notched impact strength	-30 °C	kJ/m ²	ISO 179-1eA	< 10	10
Izod impact strength	23 °C	kJ/m ²	ISO 180-1U	65	80
Izod impact strength	-30 °C	kJ/m ²	ISO 180-1U	60	55
Izod notched impact strength	23 °C	kJ/m ²	ISO 180-1A	10	20
Izod notched impact strength	-30 °C	kJ/m ²	ISO 180-1A	<10	<10
Flexural modulus	2 mm/min	MPa	ISO 178-A	8500	5000
Flexural strength	2 mm/min	MPa	ISO 178-A	270	160
Flexural strain at flexural strength	2 mm/min	%	ISO 178-A	4.0	6.0
Flexural stress at 3.5 % strain	2 mm/min	MPa	ISO 178-A	260	140
C Puncture maximum force	23 °C	N	ISO 6603-2	1000	1230
C Puncture maximum force	-30 °C	N	ISO 6603-2	860	
C Puncture energy	23 °C	J	ISO 6603-2	3	6
C Puncture energy	-30 °C	J	ISO 6603-2	3	
Ball indentation hardness		N/mm ²	ISO 2039-1	210	100
Thermal properties					
C Melting temperature	10 °C/min	°C	ISO 11357-1,-3	222	
C Temperature of deflection under load	1.80 MPa	°C	ISO 75-1,-2	200	
C Temperature of deflection under load	0.45 MPa	°C	ISO 75-1,-2	215	
Vicat softening temperature	50 N; 120 °C/h	°C	ISO 306	> 200	
C Coefficient of linear thermal expansion, parallel	23 to 55 °C	10 ⁻⁴ /K	ISO 11359-1,-2	0.2	
C Coefficient of linear thermal expansion, transverse	23 to 55 °C	10 ⁻⁴ /K	ISO 11359-1,-2	1.0	



Durethan BKV 30 H2.0 901510

Property	Test Condition	Unit	Standard	guide value	cond.
				d.a.m.	
C Burning behavior UL 94	1.5 mm	Class	UL 94	HB	
C Burning behavior UL 94	0.75 mm	Class	UL 94	HB	
C Oxygen index	Method A	%	ISO 4589-2	22	
Glow wire test (GWFI)	1.5 mm	°C	IEC 60695-2-12	700	
Burning behavior US-FMVSS302	>=1.0 mm		ISO 3795	passed	
C Vicat softening temperature	50 N; 50 °C/h	°C	ISO 306	200	
Electrical properties (23 °C/50 % r. h.)					
C Relative permittivity	100 Hz	-	IEC 60250	4.2	12
C Relative permittivity	1 MHz	-	IEC 60250	3.8	4.4
C Dissipation factor	100 Hz	10 ⁻⁴	IEC 60250	100	2550
C Dissipation factor	1 MHz	10 ⁻⁴	IEC 60250	170	780
C Volume resistivity		Ohm·m	IEC 60093	1E13	1E10
C Surface resistivity		Ohm	IEC 60093	1E14	1E13
C Electric strength	1 mm	kV/mm	IEC 60243-1	35	30
C Comparative tracking index CTI	Solution A	Rating	IEC 60112	425	
Other properties (23 °C)					
C Water absorption (Saturation value)	Water at 23 °C	%	ISO 62	7.0	
C Water absorption (Equilibrium value)	23 °C; 50 % RH	%	ISO 62	2.1	
C Density		kg/m ³	ISO 1183	1360	
Bulk density		kg/m ³	ISO 60	700	
Processing conditions for test specimens					
C Injection molding-Melt temperature		°C	ISO 294	280	
C Injection molding-Mold temperature		°C	ISO 294	80	
Processing recommendations					
Drying temperature dry air dryer		°C	-	80	
Drying time dry air dryer		h	-	2-6	
Residual moisture content		%	Acc. to Karl Fischer	0.03-0.12	
Melt temperature (Tmin - Tmax)		°C	-	270-290	
Mold temperature		°C	-	80-120	

C These property characteristics are taken from the CAMPUS plastics data bank and are based on the international catalogue of basic data for plastics according to ISO 10350.



Durethan BKV 30 H2.0 901510

Disclaimer

Standard Disclaimer

The manner in which you use and the purpose to which you put and utilize our products, technical assistance and information (whether verbal, written or by way of production evaluations), including any suggested formulations and recommendations, are beyond our control. Therefore, it is imperative that you test our products, technical assistance and information to determine to your own satisfaction whether they are suitable for your intended uses and applications. This application-specific analysis must at least include testing to determine suitability from a technical as well as health, safety and environmental standpoint. Such testing has not necessarily been done by us. Unless we otherwise agree in writing, all products are sold strictly pursuant to the terms of our standard conditions of sale. All information and technical assistance is given without warranty or guarantee, and is subject to change without notice. It is expressly understood and agreed that you assume and hereby expressly release us from all liability, in tort, contract or otherwise, incurred in connection with the use of our products, technical assistance and information. Any statement or recommendation not contained herein is unauthorized and shall not bind us. Nothing herein shall be construed as a recommendation to use any product in conflict with patents covering any material or its use. No license is implied or in fact granted under the claims of any patent.

Typical Properties

Property data is provided as general information only. Property values are approximate and are not part of the product specifications.

Flammability

Flammability results are based on small-scale laboratory tests for purposes of relative comparison and are not intended to reflect the hazards presented by this or any other material under actual fire conditions.

Health and Safety

Appropriate literature has been assembled which provides information concerning the health and safety precautions that must be observed when handling LANXESS products mentioned in this publication. Before working with these products, you must read and become familiar with the available information on their hazards, proper use, and handling. This cannot be overemphasized. Information is available in several forms, e.g., material safety data sheets (MSDS) and product labels. Consult your LANXESS Corporation representative or contact the Product Safety and Regulatory Affairs Department at LANXESS. For materials that are not LANXESS products, appropriate industrial hygiene and other safety precautions recommended by their manufacturer(s) must be followed.

Regulatory Compliance

Some of the end uses of the products described in this brochure must comply with applicable regulations, such as the FDA, NSF, USDA and CPSC. If you have any questions on the regulatory status of any LANXESS engineering thermoplastic, consult your LANXESS Corporation representative or contact the LANXESS Regulatory Affairs Manager.

Color and Visual Effects

Type and quantity of pigments or additives used to obtain certain colors and special visual effects can affect mechanical properties.

LANXESS Corporation | Pittsburgh, PA 15275

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Appendix 3

PRODUCT INFORMATION

Glass fiber reinforced Grade

KOPA[®] KN133G50

Polyamide 6 resin

Glass fiber reinforced grade

Property	Test Method	Units	Value
Physical			
Specific Gravity	ASTM D792	-	1.50
Shrinkage	ASTM D955	%	0.4~0.5
Water Absorption 23°C, Equilibrium 60%RH	ASTM D570	%	0.3
Thermal			
Melting Point	ASTM D3418	°C	220
Heat Deflection Temperature under Load	ASTM D648		
HDT/A 0.45 MPa (4.6 kg/cm ²)		°C	212
HDT/A 1.82 MPa (18.6 kg/cm ²)		°C	210
Coeff. Of Linear Thermal Expansion	ASTM D696	× 10 ⁻⁴ cm/cm·°C	0.3
Flammability	UL 94		HB
Mechanical			
Tensile Strength 23°C	ASTM D638	MPa (kg/cm ²)	205 (2,100)
Tensile Elongation 23°C	ASTM D638	%	4
Flexural Strength 23°C	ASTM D790	MPa (kg/cm ²)	335 (3,400)
Flexural Modulus 23°C	ASTM D790	MPa (kg/cm ²)	12,250 (125,000)
Notched Izod Impact Strength 23°C	ASTM D256	J/m (kg·cm/cm)	176 (18)
Rockwell Hardness R scale	ASTM D785	g/cc	120
Electrical			
Arc Resistance	ASTM D495	sec	130
Dielectric Constant	ASTM D150	10 ⁶ Hz	3
Dielectric Strength	ASTM D149	KV/mm	21

The information provided in this data sheet is based on our present state of knowledge and is estimated by KOLON PLASTICS, Inc. This information should not be used as guaranteeing specification limits. KOLON PLASTICS, Inc. make no warranty and liability in connection with any use of this information.


KOLON PLASTICS, Inc.

 KOLON TOWER, 1-23, BYULYANG-DONG, GWACHEON-CITY GYUNG GI-DO, KOREA
 More information : www.kolonplastics.com/eng/home

Appendix 4

SPECIFICATIONS OF TN SERIES MACHINES

IMM9
0190

330

IMM12
3Mies

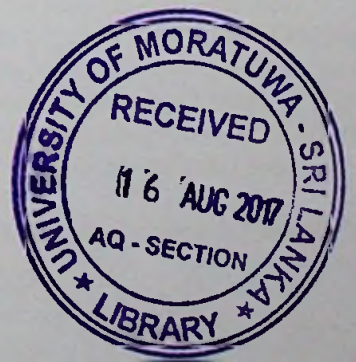
Machine Model	65 TN		105 TN		145 TN		185 TN		255 TN		315 TN		405 TN		515 TN		625 TN	
Injection Unit	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Screw Diameter mm	30	35	35	40	45	50	50	60	55	65	65	75	75	85	80	90	90	100
Shot Weight (PS) g	75	100	130	170	265	327	353	508	523	732	821	1093	1113	1430	1470	1861	2118	2615
Shot Weight (PS) oz	2.7	3.6	4.6	6	9.4	12	13	18	19	26	29	39	39	50	52	66	75	92
Max. Inj. Pressure kg.cm ²	2333	1714	2507	1919	2488	2016	2016	1400	1917	1373	1714	1288	1753	1364	1706	1348	1814	1470
Screw L/D Ratio L/D	20	17.1	20	17.5	20	18	20	16.7	20	17	20	17.3	20	17.6	20	17.7	20	18
Screw Stroke mm	117		150		185		200		245		275		280		325		370	
Screw Speed Range r.p.m.	10-184		10-232		10-200		10-150		10-170		10-170		10-175		10-150		10-152	
Nozzle Retract Stroke mm	225		250		300		320		350		400		450		500		550	
Heating Capacity kw	6.15		7.9		10.5		12.6		14.75		20.75		25		30		40	
Locking Unit																		
Max. Locking Force tonne	65		105		145		185		255		315		405		515		625	
Max. Opening Stroke mm	260		300		365		430		500		570		675		800		900	
Min. Mould Height mm	115		135		135		165		195		195		245		250		250	
Max. Mould Height mm	330		360		410		460		510		580		685		820		910	
Max. Daylight mm	590		660		775		890		1010		1150		1360		1620		1810	
Space between Tie Bars mm	325 x 325		355 x 355		410 x 410		480 x 480		616 x 550		620 x 620		690 x 690		770 x 770		903 x 861	
Max. Hyd. Ejector Stroke mm	75		100		125		125		125		150		150		250		250	
No. of Ejector Points qty	1		1		3		5		13		13		13		13		17	
General																		
Installed Ele. Capacity kw	13.65		18.9		25.5		31.1		36.75		50.75		62		75		95	
Pump Driving Motor kw	7.5		11		15		18.5		22		30		37		45		55	
Pump 'P' Max. kg.cm ²	175		175		175		175		175		175		175		175		175	
Oil Filling l	200		200		200		300		400		440		600		1000		1000	
Machine Dimensions m	3.4 x 0.9 x 1.7		3.9 x 1.0 x 1.8		4.4 x 1.1 x 1.9		5.1 x 1.2 x 2		5.9 x 1.3 x 2.1		6.5 x 1.5 x 2.2		7.7 x 1.6 x 2.4		8.4 x 1.8 x 2.6		9.2 x 2.1 x 2.7	
Shipping Dimensions m	3.62 x 1.05 x 1.7		3.84 x 1.1 x 1.7		4.4 x 1.18 x 1.91		5.3 x 1.31 x 2.06		5.83 x 1.44 x 2.13		6.64 x 1.75 x 2.18		7.62 x 1.76 x 2.45		9.37 x 1.94 x 2.57		9.88 x 2.18 x 2.82	
Machine Weight tonne	2.5		3.5		4.5		7.5		10		15		19.5		30		36	

P. 2

We reserve the right to alter any details of specifications and equipment without prior notice

Table 1.1 Specification Data Sheet

Appendix 5



Tensile Properties of Semi-Crystalline Thermoplastics – Performance Comparison under Alternative Testing Standard

ABSTRACT

Due to the wide and ever increasing application of thermoplastic parts in the automotive industry, the measurement and interpretation of their properties must be thoroughly understood before anyone can hope to correctly utilize the results in material selection, product design, and performance analysis while all these can be greatly influenced by the end-use conditions.

Tensile properties of thermoplastics, such as stress and strain at yield, ultimate tensile strength, and Young's modulus, are among the most widely measured and cited mechanical properties for material evaluation, quality control, structure design, modeling, and failure analysis. This paper deals with several major challenges that an engineer may face when attempting to obtain accurate tensile property data for thermoplastics. One such challenge is the trend of automotive industry today to convert from ASTM to ISO procedures for thermoplastics evaluation and product certification.

Our study on the widely used, semi-crystalline polyamides (PA 6) based plastics indicates that, while in most cases the values of tensile properties produced using the two standards are close, difference does exist which might be a result of different specimen geometry, and in some cases different definitions of parameters.

Another challenge is the variation in the material's properties due to the changing environment. In this investigation the tensile properties of PA 6 were studied under two environmental conditions that have the most influence on the structures in use: temperature (from -40°C to 150°C) and relative humidity (dry-as-molded (DAM) and 50% RH). The ultimate tensile strength and Young's modulus have been found to decrease significantly as the temperature or moisture level increases. However, the materials become less sensitive to the environment at elevated temperature or with high moisture content.

Results from this paper should help designers to accurately interpret tensile strength and deformation properties for the semi-crystalline thermoplastics in general and to utilize the material parameters under the end-use conditions for the structural analysis of thermoplastic components.

INTRODUCTION

IMPACT OF ISO AND ASTM TESTING STANDARDS ON TENSILE PROPERTIES OF PLASTICS

In recent years, demands have increased in using polyamide (PA) to replace certain metals and thermosets in the automotive vehicle air induction and power train systems, and lawn / garden and power tools. The combined goal in high performance, weight reduction, and time / cost savings often pushed the structures to perform toward the limit of their properties. The accurate measurement of the material properties, therefore, has become more critical than ever [1-3].

In this regard, global standardization has been playing a more important role in facilitating product manufacturing, marketing, and sales [1-2]. The widely published testing procedures and specifications for plastic materials by the American Society for Testing and Materials (ASTM, Committee D-20 on Plastics) and the International Standard Organization (ISO) have helped product developers, designers, and molders to establish correct and useful baselines. An important development in the standardization area is the fact that the American automotive industry has become one of the first to require ISO test procedures for material and product qualifications [2] when the majority of testing in the North America is still conducted using ASTM standards. The United States Council for Automotive Research (USCAR) recommended the manufacturers of thermoplastic products to fully convert to ISO test procedures by June 1998.

The decision for this conversion will no doubt have a major impact on plastic manufacturers, part molders, designers, and

end users when most of the material and product information accumulated for decades and still in use was obtained using ASTM procedures. This paper is part of our effort in assisting this transition [3]. The tensile properties of thermoplastics were analyzed not merely to compare the ASTM and ISO tensile test procedures; they were done also because of the importance of tensile properties in the product design [4-6].

The current investigation has been focused on the short-term (tensile) property evaluation of PA based thermoplastics with the influence of moisture and temperature (from -40 to 150 °C) effects. Material parameters obtained using ISO and ASTM specimens and test procedures were compared for their similarities and differences. Analyses were also made on two important aspects of the tensile property measurements, one was the use of extensometer, and another, the effect of grips and gripping on the accuracy of Young's modulus. The purpose of the investigation was to provide the plastic part designers, product developers, and testing community alike with the guidance in correctly obtaining and interpreting their tensile test results.

MOISTURE EFFECT

One of the insidious disadvantages of certain plastics, such as polyamides, is their tendency to absorb moisture from ambient, then change their properties as a result [4-7]. The moisture may exist during polymerization and washing steps in polymer processing; it can be absorbed from surrounding atmosphere during storage and use. The moisture is known to affect a range of polymer properties, which in turn impact processability, dimensional stability, mechanical, acoustic, electrical, optical, and chemical properties, as well as performance of the products [6-7].

Under dry-as-molded (DAM) conditions, polyamides, or nylon, usually contain 0.1-0.3% water. Under room temperature and 50% relative humidity (RH), type 6 polyamide could eventually absorb 2.75% water. Every 1% moisture increase in nylon may result in 0.2 to 0.3% increase in its dimension [4]. This change in dimension can be accommodated by preconditioning parts prior to service.

The moisture in nylon behaves as a plasticizer that reduces the entanglement and bonding between molecules, therefore increases their volume and mobility [7]. An increase in moisture lowers a material's strength and stiffness, but increases its total elongation and impact resistance. Practically, the best way to minimize the moisture uptake is to select plastics with low absorption rate or design products in ways to prevent excessive absorption.

The design and analysis (i.e., linear and non-linear FEA) of critically stressed nylon components require input of short and long-term mechanical properties, including effects of moisture, time-temperature, and other typical end-use environmental conditions [8-10]. The properties listed in CAMPUS® (*Computer Aided Material Preselection by Uniform Standards*) include tensile properties of plastics at two material states: dry as molded (DAM) and at 50% RH (relative humidity) at different temperatures [1, 6, 9-10]. CAMPUS®, trade literature, and design manuals normally report properties at 50% RH, which is the environment where most of the materials are conditioned prior to test. Yet reporting RH is not the same as reporting moisture, and the moisture is what directly impacts properties. This issue can be even a greater concern when testing is conducted at elevated temperatures when neither the surrounding RH nor the real moisture level in the material sample is controlled or monitored [1-2]. As the moisture in the sample is being continuously driven out by heat, one may observe significant variations in measured properties [11-13]. This paper is attempted to address some of these moisture/temperature related issues.

MATERIALS

The thermoplastics used in this investigation were heat stabilized, unfilled and glass and/or mineral filled polyamide (PA) 6. Materials were injection molded into ISO multipurpose (ISO 3167) and ASTM Type 1 and Type 2 (ASTM D 638) specimens according to the procedures specified in ISO 294-1, ISO 294-2, ASTM D 3641 and ASTM D 4066. All specimens were sealed (see ASTM D 3892) prior to testing in order to maintain their dry-as-molded (DAM) conditions.

TEST PROCEDURES

TENSILE TESTS (ISO AND ASTM PROCEDURES)

The tensile property tests were conducted using Instron 4505. Most tests were conducted under standard laboratory conditions (temperature = $23 \pm 2^\circ\text{C}$; relative humidity = $50 \pm 5\%$) on dry-as-molded samples. Some samples were also

* ASTM D4066 specified for nylon 6 moisture content wt. % max "as received" equal 0.2% (moisture content measurements by ASTM D 789).

tested at different temperatures (-40°C and 150°C) using an environmental chamber attached to the Instron. The temperature inside the chamber was controlled at ± 2°C within the set point.

Two crosshead speeds were used for testing: 1 mm/min for Young's modulus, and 5 or 50 mm/min (for reinforced and non-reinforced materials, respectively) for other tensile properties such as stresses and strains at yield and break. The tensile strain was measured from the narrow section of the specimen using a clip-on extensometer (ISO 9513 and ASTM E83) with a gage length of 50.8 mm.

The test control and data acquisition were achieved using Instron Series 9 software. The material parameters for tensile properties, such as tensile strength (σ_M), tensile strain at tensile strength (ϵ_M), stress at break (σ_B) and strain at break (ϵ_B), were obtained according to the definitions in ASTM D 638 and ISO-527[†]. The Young's modulus, E , was calculated according to the definition in ISO-527, which gives

$$E = \frac{\sigma_2 - \sigma_1}{\epsilon_2 - \epsilon_1} \quad (1)$$

where $\epsilon_1 = 0.0005$, $\epsilon_2 = 0.0025$, and $\sigma_1, \sigma_2 =$ stresses at ϵ_1 and ϵ_2 , respectively.

REMARKS ON SAMPLE CONDITIONING

Many properties of polyamides can be impacted by their moisture content. Values of mechanical, electrical, and thermal properties are reproducible only if the moisture content in the material is under control. Because of this reason, sample conditioning is an important part of property testing and specification.

In this regard, ISO 291 defines the following two standard atmospheres for conditioning:

- "Atmosphere 23": 23/50 (temperature in °C/ relative humidity in %) as recommended for most applications;
- "Atmosphere 27": 27/65, as recommended for tropical countries.

The rate of moisture absorption is very low under "Atmosphere 23". In this environment, it would take more than a year for the moisture in an ISO 3167 multipurpose test specimen (4 mm thick) of PA 66 to reach its equilibrium. To accelerate this process, a higher temperature is required. The following moisture conditioning procedures may be applied for thermoplastics:

- ISO 291 and ASTM D 618: describe standard procedures for plastic specimens conditioning prior to test / evaluation. This standard recommend six conditioning procedures, various by environment (air atmosphere / oven, water), duration, temperature and humidity / water). For moisture sensitive nylons to condition DAM specimens prior to testing is not practical.
- ISO 62 and ASTM D 570: describes standard water absorption procedures prior specimens / parts to test / evaluation. ASTM D 570 recommend seven water absorption procedures (when plastic specimen / part is immersed in to distilled water). Procedures parameters include time (from 0.5 h to 24 h), temperature (23± 1°C, 50± 1 and of 105 to 110°C). High level of temperature (boiling of water) may affect microstructure of nylon (because glass transition temperature of nylon is below boiling point of water). This method is also not practical for plastics containing extractable elements. Some concerns may exist regarding the moisture distribution across the thickness of a specimen or part. The trade literature and manufacturers published data at 20%, 50% and 100% RH was generated using this conditioning method [4,6].

Table 1 lists the water absorption values for several selected plastics as determined by ASTM D 570 after 24 h immersion at 23°C. Equilibrium value for water absorption will be significantly higher for these plastics, as will water absorption values obtained at elevated temperatures.

Table 1: Water Absorption Values for Selected Plastics

Material	Water Absorption
----------	------------------

[†] The definitions of these parameters were considered equivalent in these two standards.

PP	< 0.01 %
PC	0.15 %
Nylon 11	0.25 %
Nylon 6	1.3 %
Cellulose Acetate	1.7 %

- ISO 483 and ASTM E 104: list of saturated salt solutions and relative humidity conditioning percent (% RH) to which they correspond at various temperatures. The data at 20%, 50% and 75% RH was generated using this conditioning method [6-7].
- ISO 1110: describes accelerated conditioning at 70°C and 62% relative humidity. The period of time for accelerated conditioning can be calculated using a simple equation. The values of mechanical properties obtained after accelerated conditioning according to this method may differ slightly from those obtained after conditioning in "Atmosphere 23" [6, 9].

MOISTURE ANALYSIS IN NYLON

Moisture analysis is critical for many manufacturing processes. In molding, testing, and end-use of thermoplastics, determining the moisture content in pellets or parts can be critically important. The equilibrium moisture in nylons may vary from 1.0 to 14 % (at 100% RH). Water absorption data for commercial available nylon is presented in Table 2.

Table 2: Influence of Relative Humidity (RH%) on Water Absorption (in %, at 23°C - air) in Non-Reinforced / Non-Filled Nylons

Type of PA	30% RH	50% RH	62% RH	100% RH
PA 46	1.4	3.8	5.0	15
PA 6	1.1	2.75	3.85	9.5
PA 66	1.0	2.5	3.6	8.5

For nylon based plastics the following moisture determination methods are used in practical and laboratories applications [4, 6-7]:

- Karl-Fischer (ASTM D 789): is based on titration with a Karl Fischer Reagent. This test is sensitive to moisture levels of 0.1% to 0.2% water (when 20 g to 30 g of sample are used typically). For higher than 0.2% moisture allow smaller sample size to be used.
- ASTM D 4019: is based on release of water vapor, which is swept by an inert carrier gas into an electrolytic cell. This method allows one to use about 2 ~ 4 g of sample to measure moisture in polyamides at a level of < 0.1%. By ASTM D 4066 a maximum moisture content (in %) in varied nylon based plastics in the range from 0.05 (nylon 46) to 0.3 (nylon 612). For nylon 6 this value is 0.2%.

- ISO 1110, ASTM D 570, and a few other methods are based on weight gain measurements. Specimens of materials whose water-absorption value would be appreciably affected by the temperatures in the neighborhood of 110°C, shall be dried in a oven for 24 h at $50 \pm 0.5^\circ\text{C}$, cooled in a desiccator, and immediately weighted to the nearest 0.001 g.

ISO 1110 recommended to determinate period of time needed for accelerate conditioning (at $70 \pm 1^\circ\text{C}$ and $(62 \pm 1)\%$ RH by simple equation as function of thickness of the specimens. Relation between absorbed moisture (in %) and time of conditioning (in hours) for different thickness of the specimens (3.2; 4.0 and 6.25 mm) is presented in Figure 1.

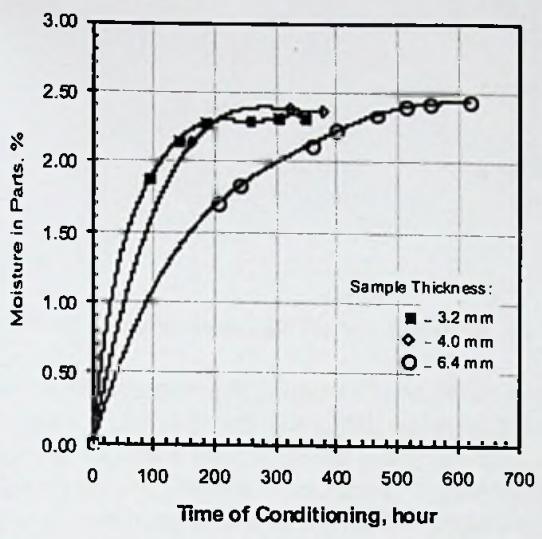


Figure 1: Moisture content vs. time of conditioning for 33 wt% glass fiber reinforced polyamide 6

This moisture-thickness-time data is very helpful for time estimation for a similar moisture content, obtained after conditioning as in the standard Atmosphere 23/50 ("Atmosphere 23").

RESULTS AND DISCUSSIONS

TENSILE PROPERTIES BY ISO AND ASTM STANDARDS AT DRY AS MOLDED (DAM) CONDITIONS

In Figures 2 to 4, properties obtained using ISO specimens were plotted against those obtained using ASTM D 638 (Type 1) specimens. The solid line, $Y = X$, indicates on the graph where the two sets of property values are equal to each other.

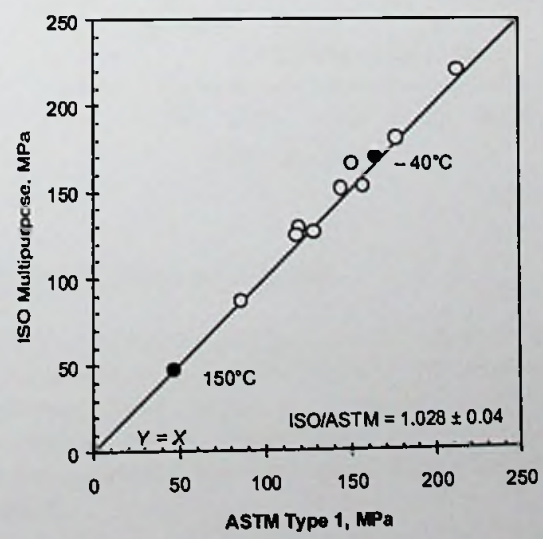


Figure 2: Tensile Strength of Materials, σ_M . $T = 23^\circ\text{C}$ unless otherwise indicated

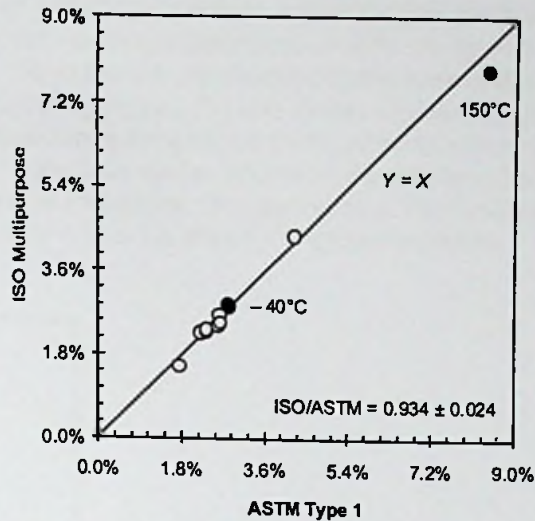


Figure 3: Tensile Strain at Tensile Strength, ϵ_M . $T = 23^\circ\text{C}$ unless otherwise indicated

For the tensile strength (Figure 2) and strain at tensile strength (Figure 3), the closeness of the data points to this line suggests that the properties obtained using the two standards are very close [3, 5, 9]. Statistically, the two sets of property values were compared using the least square method that generated a ratio between the ISO and ASTM data, as seen on each figure. The results indicate that, among the materials in the investigation, the ultimate stresses (σ_M and σ_b) obtained from ISO specimens are on average 2 ~ 3% higher than those from ASTM specimens, and 8% or more can be received from the modulus when test is done on ISO specimens. On the other hand, the opposite trend was found in tensile strains where the numbers for ϵ_M and ϵ_b are 5 ~ 6% lower in ISO 3167 specimens.

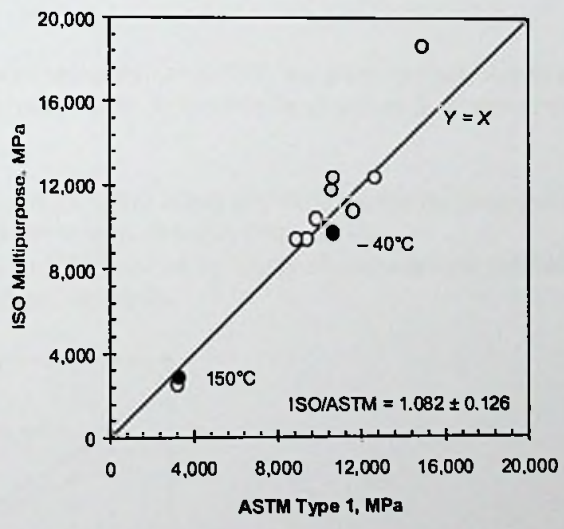


Figure 4: Young's Modulus, E. $T = 23^\circ\text{C}$ unless otherwise indicated

Despite the small difference in the nominal cross-sectional areas ($10\text{ mm} \times 4\text{ mm} = 40\text{ mm}^2$ for ISO, $12.7\text{ mm} \times 3.18\text{ mm} = 40.4\text{ mm}^2$ for ASTM Type 1), the different linear dimensions of the two specimens (e.g., the ASTM specimen is wider but thinner than the ISO specimen) might have had an impact on the injection molding process and the distribution of the reinforcement, especially the orientation and distribution of fiber-glass. If so, this may be enough to cause a difference in the measured properties. The fact that the deviation in the modulus tends to increase with the amount of glass fibers (Figure 4) further suggests such a possibility.

EFFECTS OF MOISTURE ON TENSILE PROPERTIES

Whichever standard a user may choose for testing, the properties of materials cannot be appropriately presented without

knowing the moisture content associated with the properties. In polyamides, water exists only in the amorphous phase, yet its presence could influence crystallization and crystalline phases [6-7]. In nylon 6, two crystalline types, α and γ , are known to exist. With water absorption, the γ phase is transformed to the more stable α phase. Water also behaves as a plasticizer that decreases glass transition temperature (T_g) and lowers tensile strength and Young's modulus. At room temperature (23°C), T_g for DAM nylon 6 is above the ambient [6-7]. After conditioning at 50% RH, T_g has been reduced to below ambient. Moisture and temperature have similar effects on the tensile properties. In this regard, the moisture and temperature have similar effects on the properties. The decrease in the tensile stress at the yield and increase of strains (at the yield) as function of moisture content is shown in Figure 5-moisture.

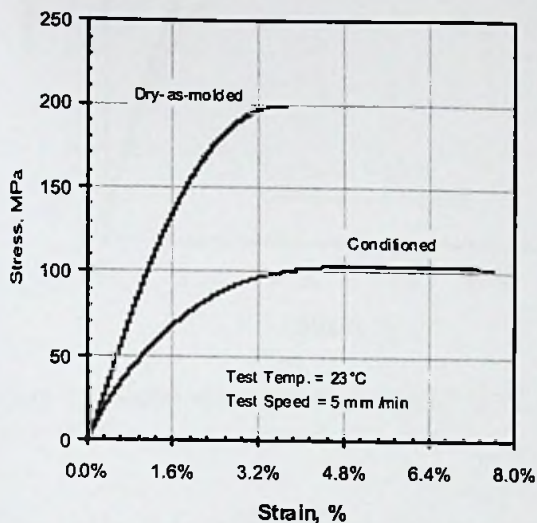


Figure 5: Tensile stress-strain curves at 23°C for 33 wt% glass fiber reinforced polyamide 6, dry-as-molded (DAM) and conditioned

At minus temperature (-40°C) and room temperature (23°C) the stress-strain curves are very similar (Figure 6). At elevated temperature (120°C) the decrease both in the tensile stress and strains at the yield and as function of moisture content is shown in Figure 7.

Changes in moisture content (from 0.2% to 1.2%) affect significantly the decrease of tensile strength and Young's modulus and increase of tensile strain at tensile strength (Figures 8).

Moisture content increase from 1.2% to 1.75% is not so highly affect to tensile properties of fiber-glass reinforced nylon 6 in comprizing with the range 0.2 – 1.2 % (Figure 9).

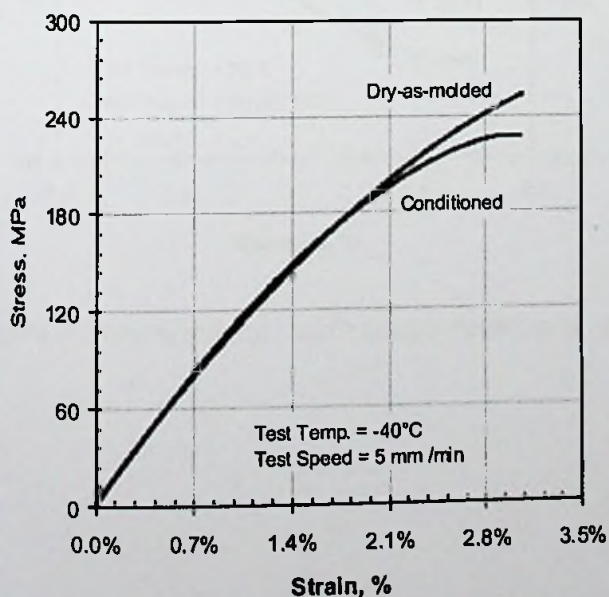


Figure 6: Tensile stress-strain curves at -40°C for 33 wt% glass fiber reinforced polyamide 6, dry-as-molded and

conditioned

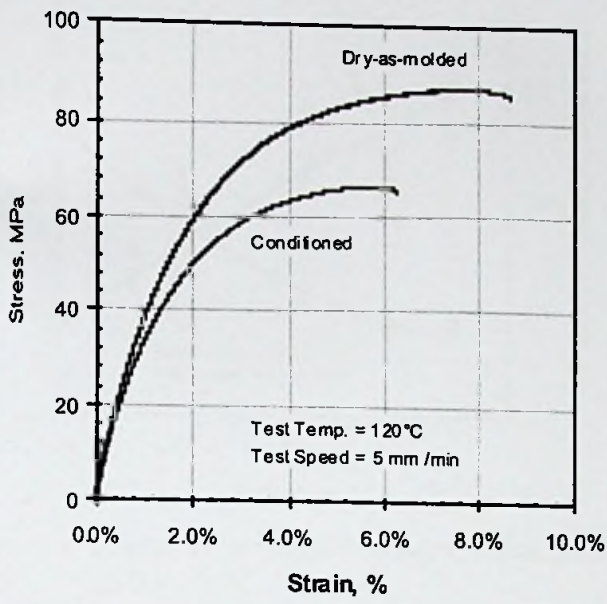


Figure 7: Tensile stress-strain curves at 120°C for 33 wt% glass fiber reinforced polyamide 6, dry-as-molded and conditioned

At this range of moisture content changes the reduction of the tensile strength is 5-6% approximately. Tensile strains will increase by 15-20%.

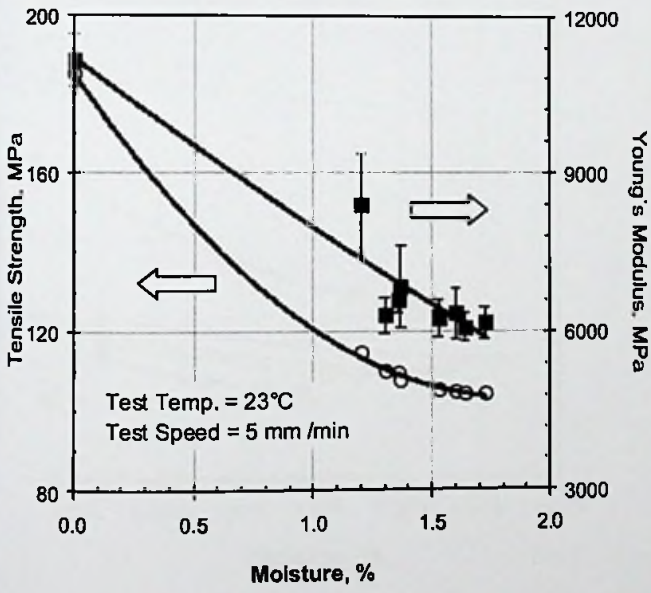


Figure 8: Tensile strength and Young's modulus vs. moisture for 33 wt% glass fiber reinforced polyamide 6



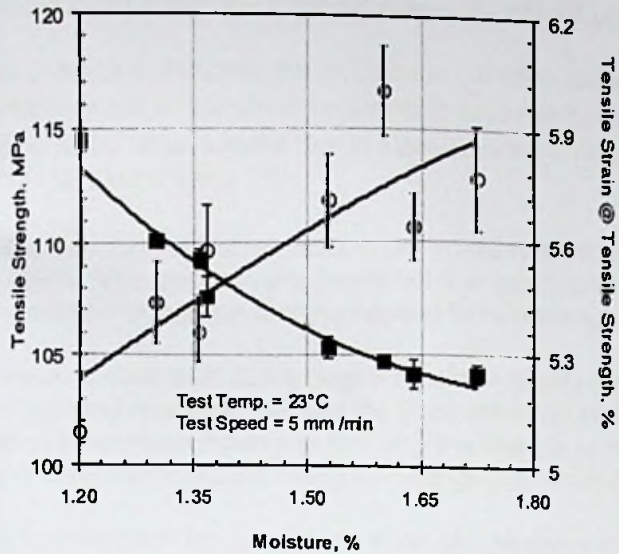


Figure 9: Change of tensile strength and tensile strain at tensile strength vs. moisture content for 33 wt% glass fiber reinforced polyamide 6

Figure 10 show changes in tensile strength of fiber-glass reinforced nylon at wide range of moisture (up to 2.7%) and temperature (-40, 23; 80; 100; 120 and 150 °C) effects. At -40°C tensile strength was changed non-significantly (decreases by 10% approximately). Very significant changes were observed at room (23°C) temperature: tensile strength decreases by 45% approximately. At elevated temperatures (from 80 to 150°C) tensile strength decrease by 20% approximately.

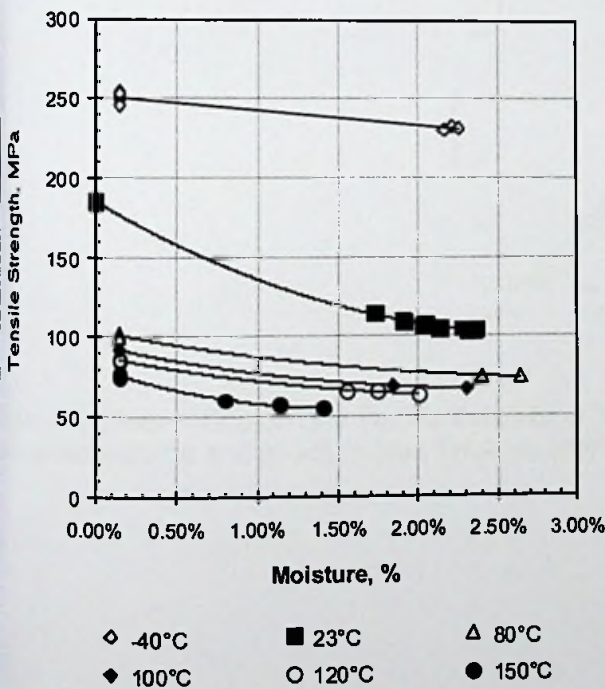


Figure 10: Tensile strength vs. moisture at different testing temperature for 33 wt% glass fiber reinforced polyamide 6

EFFECT OF GRIPS AND GRIPPING ON MODULUS MEASUREMENT

One of the observations from the tensile test was that although the sample standard deviation for stress (e.g., σ_m and σ_b) is normally very small, the same deviation is greater for strain, and greater still for Young's modulus. Using the coefficient of variation (CV) to characterize the data scattering, where $CV = (\text{sample standard deviation}) \div (\text{sample mean})$, it was

found that CV is 0.2 ~ 1.5% for stress, 2 ~ 5% for strain, and 2 ~ 10% for modulus.

In order to understand the increase in CV from stress to strain, and from strain to modulus, a closer examination was made on the stress-strain relationship between $\epsilon = 0$ and 0.3% which encloses the region where the modulus was complicated (Figure 11). It was found that in many cases the initial portion of the stress-strain curve around $\epsilon = 0$ was rather complicated (Figure 11).

The variability in the modulus could increase significantly if the initial part of the stress-strain curve extended into $\epsilon > 0.05\%$. This situation was found to be worse in some samples than in others. To find out why this was the case, the specimen elongation and the applied force were compared from one sample point to the next, as shown in Figure 11.

It was noticed that, at the beginning of the tensile test, the applied force does not always increase as the position of the crosshead changes. Instead the force remains unchanged or even decreases following an initial increase. A moment later it increases again and this time the change is more rapid. Corresponding to the force, the elongation measured by the extensometer also exhibits a strange pattern in the same region.

An explanation for this phenomenon can be given knowing that the force has been transferred to the specimen through a pair of wedge action, or self-tightening, grips. The decrease in force following an initial increase can be considered to be a result of the grips biting into the material (Figure 12). The indentation by the serrated grip faces may have caused certain plastic flow on the surface of the specimen, and it apparently has been sensed by the extensometer as suggested by the elongation behavior seen in Figure 16. The combination of the surface indentation and the surface plastic flow appears to be what gave the erroneous stress-strain behavior that in turn caused large variations in strain and modulus.

To verify this hypothesis, tensile tests were conducted on a few samples using a pair of side-action grips in which the on-going surface indentation is not an issue due to the lack of self-tightening.

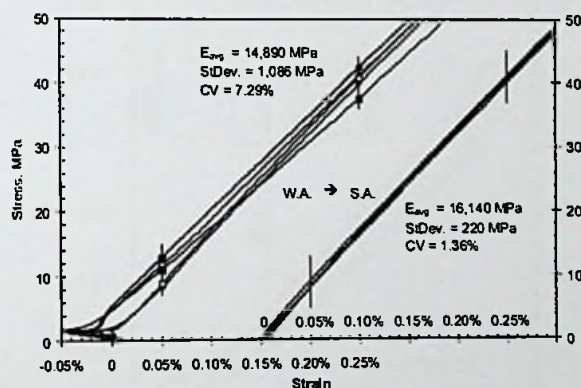


Figure 11: Effect of Grips on the Tensile Behavior of Thermoplastics (PA 6, 50% G.F.). The variation in modulus measurement associated with the wedge-action grips (W.A.) is seen to be reduced significantly with the use of side-action grips (S.A.)

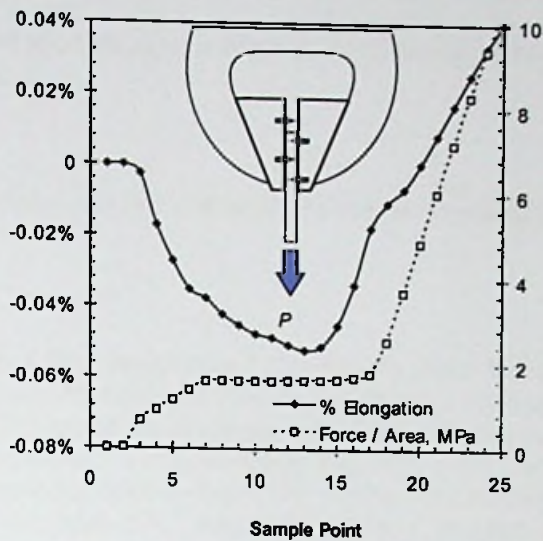


Figure 12: The Self-Tightening of the Wedge-Action Grips Was Considered to be Responsible for the Large Variability in Strain and Modulus Measurement (Figure 5)

Figure 13 shows the stress-strain in the same region as Figure 12. Sure enough, the force and elongation behavior that caused large errors is no longer there. The significantly reduced variability is obvious in Figure 12 where the stress-strain curves with wedge-action and side-action grips are compared.

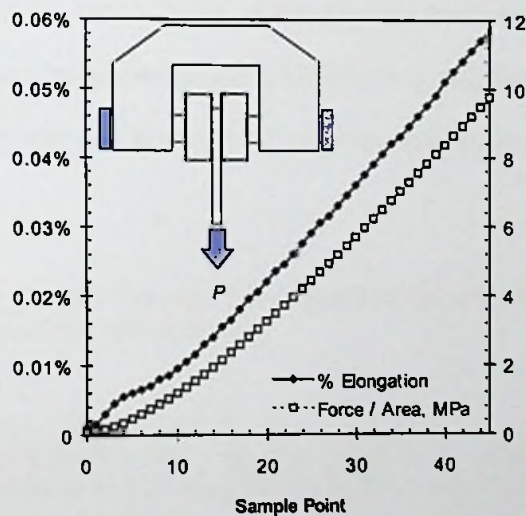


Figure 13: "Well-Behaved" Stress and Strain Curves with the Use of Side-Action Grips

CONCLUSIONS

- Tensile strength and deformation parameters of PA 6 obtained by ISO and ASTM methods are generally compatible; both can be used for the design of injection molded, non-reinforced and glass fiber reinforced parts and the material pre-selection.
- The ISO tensile stress and Young's modulus values are found to be slightly higher than those of ASTM for reinforced and non-reinforced semi-crystalline PA 6, and amorphous PP [2].
- The value of Young's modulus can be significantly affected by the method of tensile strain calculation, which can be obtained with or without an extensometer.
- Use of wedge-action grips may cause large variability in strain and modulus calculation, and this variability can be reduced significantly by using a pair of side-action grips.
- Moisture and temperature have similar effects on the tensile properties. With moisture growth tensile strength

decreases.

- Affect of moisture content on tensile strength is more effective at room temperature conditions, and is less significant at minus at elevated temperatures.

ACKNOWLEDGMENTS

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REFERENCES

1. "Uniform Global Testing Standards: A Technical Primer", The Society of the Plastics Industry, Inc., 52 pages, 1996.
2. Gabriele, C., "Global Standards Could Resolve Inconsistencies", *Plastics Technology*, pp. 48-55, June 1993.
3. Jia, N. and Kagan, V. A., "Compatibility Analysis of Tensile Properties of Polyamides Using ASTM and ISO Testing Procedures", SPE Conference Proceedings, Vol.2, Materials, pp. 1706-1712, , ANTEC'98.
4. "Engineering Plastics", *Engineering Materials Handbook*, Vol.2, ASM International, 883 pages, 1988.
5. Verne, L. "Comparable Data for Plastic Materials -- Help is on the Way", *Plastics Design Forum*, pp. 37-40, January-February 1993.
6. Kohan, M., "Nylon Plastics Handbook", Hanser / Gardner Publications, Inc., New York, 631 pages, 1995.
7. Aharoni, S., "n-Nylons: Their Synthesis, Structure and Properties", John Wiley & Sons, New York, 598 pages, 1997.
8. Jia, N. and Kagan, V. A. "Effects of Time and Temperature conditions on the Tensile-Tensile Fatigue Behavior of Short Fiber Reinforced Polyamides", SPE Conference Proceedings, Vol. 2, pp. 1844-1848, ANTEC'97.
9. Rao, N., O'Brien "Design Data for Plastics Engineers", Hanser / Gardner Publications, Inc., Cincinnati, 208 pages, 1998.
10. MacDermott, C., Shenoy, A., "Selecting Thermoplastics for Engineering Applications", Marcel Dekker, Inc., New York, 305 pages, 1997.
11. Trantina, G., Nimmer, R., "Structural Analysis of Thermoplastic Components", McGraw-Hill, Inc., New York, 366 pages, 1994.
12. Kausch, H., "Polymer Fracture: Polymers Properties and Application", Spring-Verlag Berlin Heiderberg, New York, 332 pages, 1978.
13. Deanin, R., "Polymer Structure, Proprties and Applications", Cahners Books, Boston, 496 pages, 1982.

KEYWORDS

Nylon; polyamide; plastic; stress-strain; Young's modulus; thermoplastics; tensile; moisture; absorption; water; relative humidity; conditioning; temperature, fiber-glass; reinforcement.

ABBREVIATIONS

BK – carbon black; GF – fiber-glass reinforcement; IM – impact modified; MF – mineral filled; PA – polyamide; RH – relative humidity; ASTM – American Society of Testing and Materials; ISO – International Organization for Standardization.

TERM

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

Conditioning atmosphere – the atmosphere in which a sample / plastic part is kept before being subjected to test.

Test atmosphere – the atmosphere to which a sample / plastic part is exposed throughout the test.

Moisture absorption – the pickup of water vapor from air by a material, in reference to vapor withdrawn from the air only, as distinguished from water absorption which is the gain in weight due to the absorption of water by immersion.

The water absorption may be expressed in the following ways:

- as the mass of water absorbed;
- as the mass of water absorbed per unit of surface area;

- as a percentage by mass of water absorbed with the respect to the mass of the test specimen.

Moisture content – the amount of moisture in a material determined under prescribed conditions and expressed as a percent of the mass of the moist specimen, that is, the mass of the dry substance plus the moisture.

Moisture equilibrium – the condition reached by a sample when it no longer takes up moisture from, or gives up moisture to, surrounded environment.

Moisture regain – the moisture in material determined under prescribed conditions and expressed as a percent of the weight of the moisture-free specimen. Moisture regain may result from either sorption or de-sorption, and differs from the moisture content only in the basics used for calculation.

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