MACHINE DESIGN

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Penton

PICKING A WINNING NYLON FOR THE ROLLER DERBY

Designers sometimes view all grades of nylon as the same. But when comparisons are made, cast nylon 12 often tops the list for machined rollers put to the test in harsh environments.

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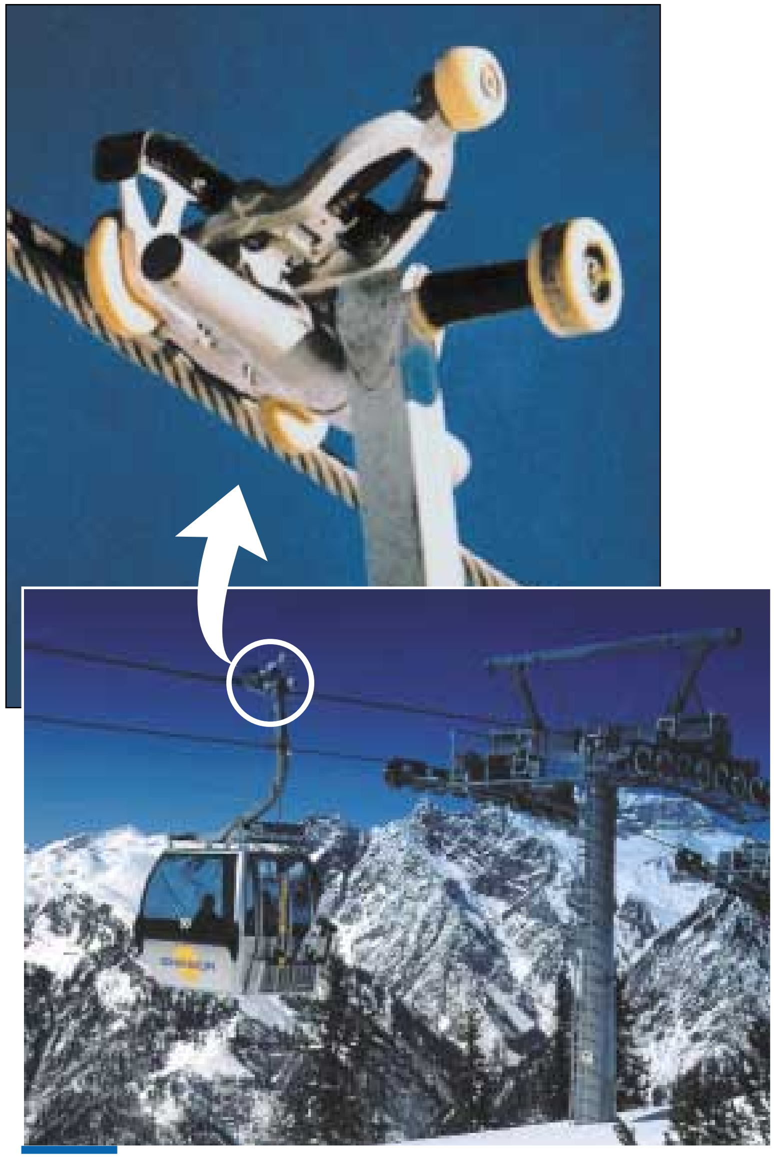
One of the most misleading material names in the industry today is nylon. Originally, the name was used by DuPont to describe a family of polyamides the company developed back in the 1930's. These materials, also referred to as PAs, were a breakthrough in man-made materials. After a short period of rapid development, they became the first engineering thermoplastics to have a highly desirable crystalline structure.

The name nylon, however, became synonymous with all PAs regardless of the manufacturer. Type in "nylon" on the Internet or consult a product guide, and you soon see that a multitude of formulations are available. The wide array often leaves designers at a loss to pick the best nylon for a particular application.

Property values among commercial grades vary because of the many formulations available. In general, however, nylons have excellent fatigue resistance and low coefficients of friction which lead to the materials being referred to as "self-lubricating." They also have good toughness depending on the degree of crystallinity in their structures. As a class of resins, they are resistant to a wide range of fuels, oils, and chemicals. But because their properties vary widely, more often than not they are specified in an incomplete fashion, resulting in confusion on the part of designers and vendors alike. This sometimes leads to parts that are not durable enough for applications used in extreme environments.

The family of nylons consists of a number of different types, some of the most common being nylon 6, 6/6, 11, and 12. The first material com-



Many ski lift manufacturers use cast nylon 12 guide and coupling rollers in their automatic rope clamping mechanisms. When the gondola enters the terminal, it is uncoupled from the steel cable and is placed on a guide rail. This slows the gondola to a comfortable speed so passengers can disembark. The coupling rollers are subjected to high shock loads during the uncoupling action. The resistance of cast nylon 12 to flat development even under varying environmental conditions, such as changes in temperature, humidity, and UV exposure, means that despite the long period of downtime during the off season, roller performance is not affected when the lift is put into service in the winter.

Water absorption in common nylons

TYPE	MOISTURE CONTENT @ EQUILIBRIUM (%) WITH 50% R.H.	MOISTURE CONTENT @ SATURATION (%)
6	2.7	9.5
6/6	2.5	8.0
6/10	1.5	3.5
6/12	1.3	3.0
11	0.8	1.9 to 2.9*
12	0.7	1.4 to 2.5**

* varies with temperature. **includes cast nylon 12.

mercially produced in 1939 by the DuPont plant in Seaford, Del., and given the trade name "nylon," was actually polyhexamethylene adipamide. It was also known as nylon 6/6 for the presence of six carbon atoms in each of its two molecules or monomers.

Monomers react with other monomers of the same or with monomers of a different compound to form very large molecules, or polymers. Soon after the DuPont discovery, Europeans followed suit with so-called nylon 6, which was based on the polymerization of a single reactant, a lactam resin called caprolactam.

The number of carbon atoms within monomers such as diamines and diacids, or in single reactants such as amino acids or lactams, provides the numerical identification of the nylon grade. The specific chemical composition is one of the variables giving each grade its particular physical characteristics. Nylons such as the 6/6 versions are made from two monomers and are commonly referred to as AABB polymers. Nylons derived from single reactants are AB polymers. Nylon 6 and 12 are examples of AB-type polymers.

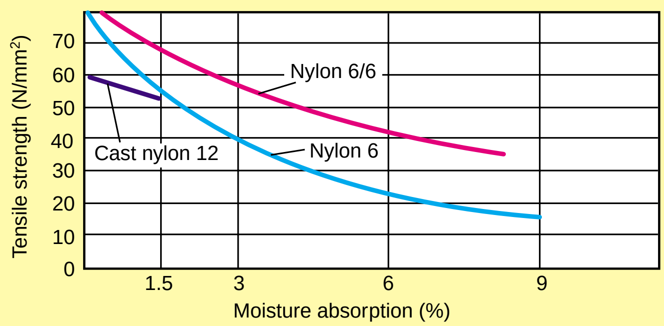
Another dominant characteristic affecting physical properties of nylon is the homogeneity of crystallinity within the material. It is responsible for key properties such as toughness, fatigue resistance, and high-temperature stability. Creep resistance and moisture absorption are also influenced by the degree of crystalline and amorphous or noncrystalline regions within the material. With increasing crystallinity, nylon's stiffness or elastic modulus, density, chemical and abrasion resistance, and strength increase. Similarly, other related attributes such as hardness, yield point, and dimensional stability are also enhanced. On the other hand, properties such as thermal expansion, elongation, and swelling decrease. And although impact strength begins to decrease with higher crystallinity, new processing techniques minimize this decline.

Water is another factor influencing the physical properties of each grade.

The higher the crystallinity, the lower the water absorption. Water acts as a plasticizer, and in many respects, exposing nylon to water has the same effects as raising the temperature by a substantial amount.

The rate of crystallinity and water absorption are directly related. All nylons absorb moisture from the environment at varying degrees and at different rates. The equilibrium moisture content of a nylon depends mostly on amide-group concentration, crystallinity, relative humidity, and temperature. Excessive moisture absorption leads to dimen-

Moisture absorption versus tensile strength



With moisture absorption, tensile strength of nylon 6 can drop to below 20%, while for cast nylon 12 it remains stable within 90% of its original value.

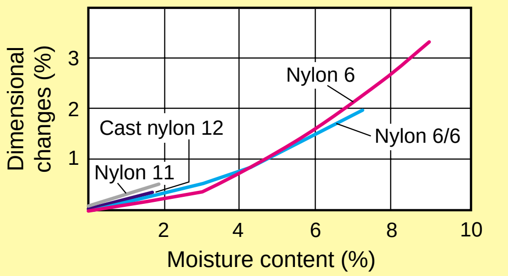
Typical unreinforced nylon property ranges

PROPERTIES	6*
PHYSICAL	**AVERAGE (range)**
Density, gm/cc	1.13, (1 to 1.17)
Linear mold shrinkage cm/cm	0.12, (0.006 to 0.0185)
Hardness R_R	110, (78 to 120)
MECHANICAL	
Tensile strength, yield (MPa)	63.8, (20 to 95)
Tensile strength, ultimate (MPa)	69.5, (48 to 100)
Modulus of elasticity, (GPa)	2.0, (0.3 to 4)
Flexural modulus, (GPa)	2.1, (0.1 to 3.4)
Impact strength, Izod, (J/cm)	2, (0.37 to 10)
THERMAL	
Coefficient of thermal expansion, linear 20°C, μm/m-°C	90.7, (70 to 200)
Deflection temperature at 0.46 MPa, °C	160, (50 to 198)
Deflection temperature at 1.8 MPa, °C	63, (40 to 83)
Melting point, °C	220, (193 to 231)

*Does not include cast nylons.

The above information is from overviews of nylon types as posted on the www.MatWeb.com database. MatWeb periodically calculates average values and min/max ranges from all of the proprietary plastics in the database and reports the data in overviews of 700 plastic types. Note that the property comparison table represents only

Dimensional change polyamides versus moisture



Moisture absorption causes swelling which results in up to 3.3% dimensional change in the nylon 6 family. When designing with nylon 6 or 6/6, this has to be taken into consideration, for example, when calculating backlash in gears, or when storing precision parts for prolonged periods of time in changing environments. For cast nylon 12 such change is negligible, even when permanently immersed in fuels, oils, and chemicals.

Nylon 12 is gravity cast around a knurled metal core to form a blank which is then machined into gears. Metal cores are available in different sizes and materials.

sional and property changes of formed parts.

Depending on the application, moisture absorption may be one of the most critical factors to consider during material selection. For example, if a component is machined from an unspecified nylon grade to close tolerances in a comparatively dry environment, its dimensions will change if used in a humid location. The part will absorb moisture until it reaches equilibrium, and the resulting swelling will cause dimensions to go out-of-tolerance and possibly trigger premature part failure.

The common ways of forming nylon, including injection molding, extrusion, and casting, also influence material properties. In injection molding the nylon is subjected to high compression and decompression within a short period of time. Proper mold design, precise timing, and correct pressure control are crucial, as is maintaining an accurate thermal history of the part both inside and outside the mold.

In extrusion, the presence of water can cause severe problems. Therefore, moisture content as well as cooling rates must be monitored closely because they both present a major influence on the physical properties of the extrusion.

Material shrinkage is also a concern for extruded rods or slabs. Shrinkage voids sometimes are produced when the outer surface solidifies while the inside is still in a molten state. As the inside cools and shrinks due to thermal contraction and crystallization, the rigid outside can no longer shrink, and a void is formed.

To minimize this, extruders need to use controlled water or vacuum quenching to cool formed parts in a manner that depends on shape and quality required. While these forming processes can be precisely controlled, physical properties and dimensions may change over time when exposed to changing transport and storage conditions.

6/6	11*	12*
AVERAGE (range)	**AVERAGE (range)**	**AVERAGE (range)**
1.14, (1.03 to 1.27)	1.03, (1 to 1.05)	1.04, (1.01 to 1.17)
0.014, (0.006 to 0.019)	0.014, (0.014 to 0.014)	0.01, (0.007 to 0.015)
120, (93 to 125)	106, (105 to 108)	100, (67 to 110)
69.6, (40 to 100)	34.7, (15 to 44)	40.3, (24 to 78)
76.9, (43 to 94)	55.6, (41 to 69)	49.1, (38 to 56)
2.5, (0.7 to 3.9)	0.957, (0.185 to 1.58)	1.1, (0.4 to 2.9)
2.5, (0.9 to 3.4)	0.83, (0.38 to 1.4)	1.0, (0.26 to 1.6)
1.1, (0.39 to 8.5)	2.8, (0.4 to 8.0)	2.2, (0.43 to no break)
81.7, (50 to 150)	94.5, (85 to 120)	93.7, (50 to 140)
220, (85 to 243)	140, (70 to 150)	130, (95 to 160)
79.7, (50 to 99)	48.4, (40 to 55)	52.6, (45 to 135)
260, (211 to 263)	180, (175 to 191)	180, (168 to 184)

a general overview of material properties under certain conditions. For instance, not all listed properties are shown under the same conditions. Therefore, it is important to consider all factors influencing the application such as moisture absorption and temperature before selecting a material.

CASTING NYLON

Nylon 6 and 12 are available in cast forms such as bars, tubes, and plates. Shapes cast from nylon 6 are commonly used for prototyping and medium-quality components. Cast nylon 12 is generally used for precision engineering components needing properties such as dimensional stability, high-temperature toughness, and chemical resistance. Recently, nylon 6 casting processes have been refined, and the physical properties of formed components have been improved. In spite of the improvements, however, cast components made from nylon 6 often fall short when compared to those made with cast nylon 12, especially for tough applications in hostile environments. Cast nylon 12 is extremely resistant to cavitation, moisture absorption, and to

Property comparison of cast nylon 12 and cast nylon 6

PROPERTY	TEST METHOD	CAST NYLON 12	CAST NYLON 6
Density, g/cc	ASTM D792	1.03	1.15
Water absorption, %	ASTM D256	0.047	0.22
Hardness, R_R	ASTM	108	110
MECHANICAL			
Tensile strength, yield (MPa)	ASTM D638	60	69
Elongation %; break	ASTM D638	16	35
Modulus of elasticity, (GPa)	ASTM D638	2.1	2
Flexural modulus (GPa)	ASTM D790	2.1	3.4
Impact strength, (J/cm)	Charpy (+20° C)	4 to 20	0.48
Compressive yield strength, MPa	DIM53454	45	80
THERMAL			
CTE, linear 20°C, μm/m-°C	Upper limit	50	100
Deflection temperature at 1.8 MPa, (°C)	ASTM D648	175	60
Melting point, (°C)	Polarizing microscope	181	215
Coefficient of linear expansion, 1/°C	ASTM D696	9.44×10^{-5}	14.4×10^{-5}

abrasion caused by friction or fluids. It exhibits outstanding long-term behavior under high load and elevated temperatures and is easily machined to close tolerances.

There are a number of low-pressure casting methods available for nylons. One proprietary gravity casting process is developed especially to provide nylon 12's crystallization structure. During gravity casting, the mold is preheated while the resin, laurinlactam, is melted and brought to the same temperature. The melt is poured into the mold, which is placed in an oven at a specified temperature. Pouring temperatures influence the quality of casting, so proper handling of the melt prior to and during casting is important.

Mold material and construction are also crucial because heat exchange in the mold will vary with materials and mold dimensions. The oven dwell time and subsequent cooling depends on whether or not the part is a solid rod, tube, plate, or is molded around a specially prepared metal core such as that used in the construction of gear blanks.

The heat-exchange rates within the oven directly affect how the nylon will crystallize. During the period of precisely controlled cooling, long polymer chains fold up like an accordion, forming a regular repeating structure, or crystal.

During gravity casting, these crystals lump together and are much harder to break up than individual crystals. These formations, called spherolites, give cast nylon 12 superior physical properties at high temperatures when compared to their injection-molded counterparts. In a carefully controlled casting process, such as that for nylon 12, the homogeneity of the crystallization is high.

During most polymerization processes, however, a certain amount of noncrystalline or amorphous regions may be present from mismatch and other defects within the crystals. For this reason, most other nylons are actually semicrystalline. Their crystallization rate depends on grade.

Gravity casting of rods, tubes, and plates produces nylon 12 parts with a nearly perfect homogeneous crystalline structure. Casting the same material around a steel shaft for gears will drop homogeneity somewhat because thermal properties of the metal restrict the resin's ability to crystallize fully.

Nylon 6, on the other hand, generally has a much lower homogeneity rate, and while advanced casting processes may increase that rate to a higher level, other properties may suffer in the process. One material may be overkill for applications that do not place any particular demands on material properties, while the other may not be good enough for applications in a tough operating environment where dimensional stability and durability are essential qualities. Designers will have to take all parameters of their application into consideration to make the correct selection.

Because gravity casting is a low-pressure forming process where molecular chains are not subjected to force orientation, cast nylon 12 parts made by this method have little internal stress. The spherulitic crystal structure typical for cast nylon 12 is a sign of having been formed in an environment free of stress. Gravity casting eliminates the mechanical and thermal stresses that result from melt disturbance or large temperature gradients sometimes present during other forming processes.

Cast nylon 12 has a higher molecular weight and more even molecular weight distribution than the typical injection molded or extruded nylon. The gravity casting process also allows casting of tough elastic nylon 12 around a metal core with virtually no dimensional limitations other than a specific minimum wall thickness of the plastic.

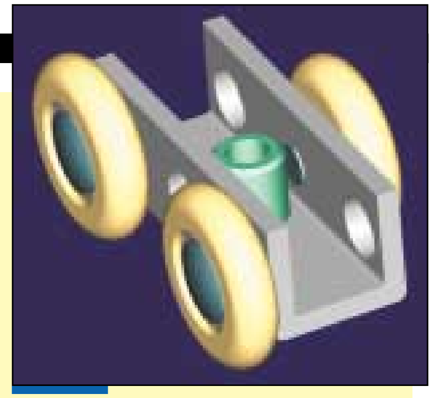
On the other hand, when nylon 6 is cast around a metal core, the inherent brittleness of the casting may cause stress cracks and put constraints on overall part dimensions and machinability. In extrusion and molding, mechanical stresses may occur when the melt is agitated, and thermal stresses may result from the parts being cooled too rapidly. If a hot casting is cooled too fast, the material's structure is literally "shocked," causing internal stresses. These stresses can produce microscopic stress cracks in the finished part, which will lead to part failure under load.

RIDING THE RAILS

Cast nylon 12's dimensional stability, low moisture absorption, and resistance to compression under static loads make it an almost ideal metal-to-plastic conversion for rollers used in hostile environments. Unlike other plastic rollers, cast nylon 12 has high resistance to deformation and good internal elasticity. These properties al-

CALCULATING THE DURABILITY OF ROLLERS

After years of collecting and analyzing experimental data, engineers have developed a durability calculation for nylon 12 rollers produced by a proprietary gravity casting process, with the resulting product referred to as Power-Core. For the calculation, required information includes not only the physical dimensions of the roller, but also as much application detail as possible. These details include operating conditions and environment, the material of the rail (or component) the roller is running against, bearing size and type, as well as minimum and maximum forces applied. Also required are speeds, cycle times, standing times, stop and go motion/shock loading, and desired roller life expectancy. In general, the calculation summary will provide information on the extent of the flat, initial rolling force required, and life expectancy under the specified conditions.



Parts such as this sliding door hanger can be optimized for best roller performance, ease of assembly, and cost effectiveness.

A proprietary algorithm developed at Intech Corp. takes into account Hertzian stress and linear speed, indicating whether or not the material is a good match for the application. For a given design the algorithm used in the calculation compares the results of the classical Hertzian stress calculation to the matrix of experimental data in the algorithm's database. Roller life expectancy is calculated in "roll overs" or hours of operation. At the same time, the rating of the selected bearing is evaluated, which allows selection of the most suitable bearing as well.

A cast nylon 12 tire is heat shrunk onto the bearing, thus ensuring a rolling motion without slippage of the bearing inside the plastic tire at high temperatures and eliminating internal stresses at low temperatures. If any of the application factors are unfavorable — for example the applied load is too high — alternate design solutions are generated from the calculation results. *—Boyka Kriakova*

Boyka Kriakova, design engineer at Intech Corp., evaluates and calculates cast nylon 12 roller designs.

Input parameters and anticipated performance summary

SAMPLE ROLLER DATA FROM XYZ COMPANY'S DRAWING

APPLICATION PARAMETERS	
Roller radius	0.625 in.
Face width	0.500 in.
Fillet radius	0.063 in.
Rail radius	Infinite
Contact width	0.375 in.
Contact length	0.024 in
Radial load	130 lb-ft
Speed	70 fpm
Duty cycle	Continuous
Temperature (min/max)	–40 to 140°F
Bearing	R6
Material damping factor	0.2
RESULTS:	
Hertzian stress	47.59 N/mm^2
Perpetual rolling force	2.6 N
ROLLER LIFE	
Roller life expectancy	100,000,000 cycles
Number of hours at 70 ft/m	8,000 hr

The sample calculation output illustrates that the roller will last 8,000 hr under the specified conditions. If the customer indicates that the duty cycle includes a stand-still time under load, for example, 8 hr/day, engineers calculate the factor by which the contact length increases, the so-called time-dependent contact length or flattening. The initial rolling force required to put the roller into motion again, in the sample case, will be approximately 4N, and the flat will be recovered after about 0.5 in. of linear motion.

low cast nylon 12 rollers to resist the development of a permanent flat when the roller is stopped for an extended period of time under heavy load.

Under static load the theoretical contact area of the roller and rail is a point or line. This relatively small area sees an extremely high compressive stress when the roller stops and may cause flattening of the roller at point of contact. The extent of the flat depends on the applied load over time. When the load exceeds the material's yield point, a permanent flat is developed, rendering the roller useless.

Any roller will always exhibit a certain amount of flattening when standing still. To overcome this flat or elastic deformation and to start rolling motion, an initial force has to be applied. After a short period of motion the flat is recovered, and the roller continues to turn under rolling force, which is much smaller than the initial starting force.

When rollers are in operation, contact stresses at any point on the roller surface are cyclically applied with each revolution. Surface fatigue failures tend to be produced when minute cracks develop on the roller surface. Operating conditions can influence the material deterioration, and the roller may start to exhibit signs of wear, or at worst, develop a permanent flat and begin to wear out the much more costly rail it is running on. ■