POLYAMIDES, PLASTICS

1. Introduction

The use of polyamides in plastic applications dates back to the original commercialization of this polymer. The first polyamide application was the introduction by DuPont in 1938 of nylon-6,6 for tooth brush filaments (1). Although fiber applications soon dominated, the use of polyamides as plastics grew steadily from the 1950s and is estimated to represent more than 25% of total polyamide use in the year 2000 or 1.65 million metric tons per year (2). Demand in 2003 reached 1.7×10^6 t (3).

Polyamides were the first engineering plastics and still represent by far the biggest and most important class of these types of material. The combination of mechanical and thermal properties allows them to be employed for highly specified end uses and often for metal replacement applications (see Engineering Thermoplastics, Survey).

Polyamides comprise a range of materials, depending on the monomers employed. Nylon-6,6 [32131-17-2] and nylon-6 [25038-54-4] continue to be the most popular types, still accounting for more than 90% of nylon use. Table 1 gives a summary of the properties of the more common types which are currently

Table 1. **Properties of the More Common Nylons, Dry as Molded**

Property	Nylon-6,6[a]	Nylon-6[b]	Nylon-11[c]	Nylon-12[d]	Nylon-6,9[e]	Nylon-6, 12[a]	ASTM test method
CAS Registry Number	[32131-17-2]	[25038-54-4]	[25035-04-5]	[24937-16-4]	[28757-63-3]	[24936-74-1]	
specific gravity	1.14	1.13	1.04	1.02	1.09	1.07	D792
water absorption, wt%							
24 h	1.2	1.6	0.3	0.25	0.5	0.25	
equilibrium at 50% rh	2.5	2.7	0.8	0.7	1.8	1.4	
saturation	8.5	9.5	1.9	1.5	4.5	3.0	
melting point, °C	255	215	194	179	205	212	D2117
tensile yield strength, MPa[f]	83	81	55	55	55	61	D638
elongation at break, %	60–90	50–150	200	200	125	150	D638
flexural modulus, MPa[f]	2800	2800	1200	1100	2000	2000	D790
Izod impact strength, J/m[g]	53–64	55–65	40–68	95	58	53	D256
Rockwell hardness, R scale	121	119	108	107	111	114	D785
deflection temperature under load, °C							D648
at 0.5 MPa[f]	235	185	150	150	150	180	
at 1.8 MPa[f]	90	75	55	55	55	90	
dielectric strength, kV/mm							D149
short time	24	17	16.7	18	24	16	
step by step	11	15		16	20		

Table 1. (*Continued*)

Property	Nylon-6,6[a]	Nylon-6[b]	Nylon-11[c]	Nylon-12[d]	Nylon-6,9[e]	Nylon-6, 12[a]	ASTM test method
dielectric constant							D150
at 60 Hz	4.0	3.8	3.7	4.2	3.7	4.0	
at 10^3Hz	3.9	3.7	3.7	3.8	3.6	4.0	
at 10^6 Hz	3.6	3.4	3.1	3.1	3.3	3.5	
starting acid[h] or lactam	adipic acid[h]	caprolactam	11-aminoundecanoic acid	dodecanolactam	azaleic acid[h]	dodecanedioic acid[h]	

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[a] Ref. 4.

[b] Ref. 5.

[c] Ref. 6.

[d] Ref. 7.

[e] Ref. 8.

[f] To convert MPa to psi, multiply by 145.

[g] To convert J/m to ft·lbf/in., divide by 53.38.

[h] The starting amine is hexamethylenediamine for nylon-6,6, nylon-6,9, and nylon-6,12.

commercially available. In recent years there has been increasing interest in polyamides with higher melting points to extend the boundaries of this polymer type to satisfy more stringent high temperature automotive and electronic applications. This has resulted in the development of nylon-4,6 and several semiaromatic nylons.

2. Physical Properties

The original development of polyamides, initially nylon-6,6 then nylon-6, concentrated on their potential as fiber-forming materials where strength, elasticity, and high dye uptake were considered the most important properties, along with the ability to withstand ironing temperatures. It soon became apparent, however, that the properties of the material held many advantages for use as a plastic. In particular, the relatively high tensile strength and stiffness, together with good toughness, high melting point (and therefore temperature stability), and good chemical resistance, all combined to allow a wide range of applications. The material soon came to be seen as an engineering plastic that could be used for metal replacement in structural or semistructural end uses. These properties are present to a greater or lesser extent in the entire semicrystalline polyamide family and form the basis for the continuing success and growth of these materials.

Appropriate choice of monomer can provide a balance of properties to meet particular types of applications. In general, the effects of different monomers and therefore the property balance of different types of nylon can be summarized as follows: lengthening the aliphatic segments between the amide groups results in lower moisture absorption, reduced strength and stiffness, and lower melting point (eg, nylon-11 or nylon-12 compared to nylon-6,6). The introduction of aromatic groups increases stiffness and strength but reduces moisture uptake and, to a lesser extent, impact strength. Some semiaromatic polyamides also have an increased melting point.

In addition to the semicrystalline nylons, which comprise the vast majority of commercial resins, nylon is also available in an amorphous form that gives rise to transparency and improved toughness at the expense of high temperature properties and chemical stress-crack resistance. Table 2 shows the properties of some different polyamide types.

2.1. Crystallinity. The presence of the polar amide groups allows hydrogen bonding between the carbonyl and NH groups in adjacent sections of the polyamide chains. For common nylons such as nylon-6,6 and nylon-6, the regular spatial alignment of amide groups allows a high degree of hydrogen bonding to be developed when chains are aligned together, giving rise to a crystalline structure in that region. These nylons are semicrystalline materials that can be thought of as a combination of ordered crystalline regions and more random amorphous areas having a much lower concentration of hydrogen bonding. This semicrystalline structure gives rise to the good balance of properties. The crystalline regions contribute to the stiffness, strength, chemical resistance, creep resistance, temperature stability, and electrical properties; the amorphous areas contribute to the impact resistance and high elongation. The crystallinity can be disrupted by substituents on the chains that interfere with the alignment process. Amorphous nylons are produced by deliberately engineering this effect, eg, nylon-NDT/INDT

Table 2. **Properties of Other Nylons, Dry as Molded**

Property	Nylon-4,6	Nylon-MXD,6	Nylon-NDT/INDT	Polyphthalamide (PPA)
CAS registry number	[50327-22-5]	[25805-74-7]	[9071-17-4]	
water absorption, %				
24 h	2.0	0.31		0.81
50% rh	3.4		3.0	
saturation	13.0	5.5	7.0	
melting point, °C	295	243	amorphous	310
glass-transition temperature, T_g, °C	~85	102	149	123–135
tensile strength, MPa[a]	95	103	85	104
flexural modulus, MPa[a]	3100	4500	2900	3300
elongation at break, %	50	2.3	70	6.4
notched Izod impact strength, J/m	110	20	~160	53
DTUL[c] at 1.8 MPa,[a] °C	160	96	130	120
starting materials				
amine	diaminobutane	*m*-xylylenendiamine	trimethylhexamethylenediamine	hexamethylenediamine
acid	adipic acid	adipic acid	terephthalic acid	adipic acid, iso/terephthalic acids
reference	9	10	11	12

[a] To convert MPa to psi, multiply by 145.

[b] To convert J/m to ft·lbf/in., divide by 53.38.

[c] Deflection temperature under load.

(also known as PA-6-3-T or PA-TMDT), which uses trimethyl-substituted hexamethylenediamine isomers combined with terephthalic acid.

2.2. Thermal Properties. The high melting point of polyamides such as nylon-6,6 is a function of both the strong hydrogen bonding between the chains and the crystal structure. This also allows the materials to retain significant stiffness above the glass-transition temperature (T_g) and almost up to the melting point. The effect is further increased when reinforcements such as glass fiber are added, giving a high deflection temperature under load even at high loading. The effect also results in the sharp melting points of nylon as the majority of the hydrogen bonding rapidly breaks down at that temperature, giving a low viscosity, water-like melt. The melting point is mainly related to the degree of hydrogen bonding between the chains, which depends on the density of amide groups. The melting point therefore drops as the length of aliphatic groups between the amide links increases (eg, nylon-6,6 melting at

264°C, compared to nylon-6,12 at 212°C). The influence of structure on the melting point is further complicated by factors that affect the ease of crystallization. For even–even nylons such as nylon-6,6 and nylon-6,12, the monomers have a center of symmetry and the amide groups easily align to form hydrogen bonds in whichever direction the chains are facing when placed on top of one another. For even nylons, such as nylon-6, that have no center of symmetry, the amide groups are in the correct positions only if the chains are aligned in one particular direction (antiparallel). For this reason, nylon-6 has a melting point more than 40°C lower than nylon-6,6, despite having the same density of amide groups. It also has a slower crystallization rate and therefore wider processing window. Other types of nylon, such as even–odd and odd nylons, also differ from the above types for similar reasons of crystallization and crystal packing. In addition, crystallization is impeded and melting point reduced by copolymerization and substituents on the chains, although in certain cases isomorphism of comonomers avoids this effect, eg, terephthalic acid increases the melting point of nylon-6,6.

In recent years, polyamides have been increasingly used in higher temperature applications (mainly automotive) and in addition to the newer high melting point materials, glass-reinforced nylon-6,6, in specially modified formulations, has been shown to be suitable for use in replacing metals at temperatures which would not have been considered possible a few years ago (13).

2.3. Moisture Absorption.

A characteristic property of nylon is the ability to absorb significant amounts of water (14) (Fig. 1). This again is related to the polar amide groups around which water molecules can become coordinated. Water absorption is generally concentrated in the amorphous regions of the polymer where it has the effect of plasticizing the material by interrupting the polymer hydrogen bonding, making it more flexible (with lower tensile strength) and increasing the impact strength. The T_g is also reduced. Moisture absorption, determined by both the degree of crystallinity and the density of amide groups, is, as with the melting point, reduced with increasing length of aliphatic groups in the chain. Aromatic monomers also reduce the moisture absorption. Nylon-6 has a higher moisture absorption than nylon-6,6 because of its lower crystallinity. The effect of moisture absorption on the mechanical properties of nylon-6,6 is included in Table 3.

2.4. Electrical Properties.

Nylons are frequently used in electrical applications mainly for their combination of mechanical, thermal, chemical, and electrical properties. They are reasonably good insulators at low temperatures and humidities and are generally suitable for low frequency, moderate voltage applications. The relatively high dissipation factor of nylon causes problems under conditions of high electrical stress, particularly when moist, because of the likelihood of overheating. Dry nylon has volume resistivities in the 10^{14}–10^{15} $\Omega\cdot$cm region, but this decreases with increasing moisture and temperature. Dielectric constant displays large increases with moisture and temperature. For moist nylon, however, the value decreases with increasing frequency, as the water molecules are less able to respond at higher frequencies.

Nylons have excellent arc and tracking resistance. Arc resistance is not affected by moisture or temperature up to about 100°C. Comparative tracking resistance of most unmodified nylons is greater than 600 V. Incorporation of

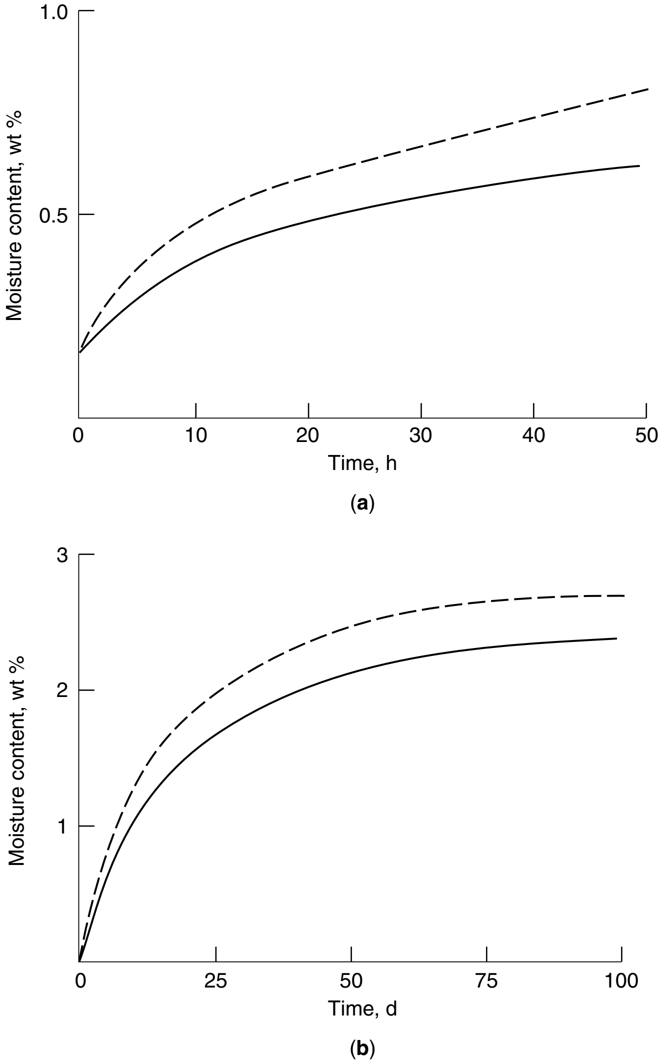

Fig. 1. Rate of moisture pickup for nylon-6,6 (—) and nylon-6 (– – –) granules at 50% rh and 23°C: (**a**) 0–48 hours; (**b**) 0–100 days.

additives such as flame retardants often reduces the electrical properties because of the introduction of ionic species.

2.5. Flammability. Most nylons are classified V-2 by the Underwriters' Laboratory UL-94 test, which means that these nylons are self-extinguishing within a certain time scale under the conditions of the test. They achieve this performance by means of giving off burning drips. Inclusion of reinforcement such as glass fiber converts this behavior to HB, where the sample continues to burn as a result of the reinforcement holding it together. The flammability performance can be improved by adding flame-retardant additives that can eliminate burning drips and produce nylon that meets the most stringent UL-94 test (V-0), even with materials containing glass fibers.

Table 3. **Effect of Additives on Nylon-6,6 and Nylon-12**

		Nylon-6,6 +			
Property	Nylon-6,6[a]	30 wt% Glass fiber[a]	Impact modifier[a]	Nylon-12[b]	Nylon-12 + plasticizer[b]
tensile strength, MPa[c]					
dry	83	193	52	50–55	27
50% rh[d]	77	130	41		
flexural modulus, MPa[c]					
dry	2800	9300	1800	1500	330
50% rh[d]	1200	6600	900		
elongation at break, %					
dry	60	3	60	200	300
50% rh[d]	>300	5	210		
notched Izod impact strength, J/m[e]					
dry	53	110	910	60	no break
50% hr[d]	112	133	1070		
deflection temperature under load at 1.8 MPa[c], °C	90	254	83	50	55

[a] Ref. 4.

[b] Ref. 7.

[c] To convert MPa to psi, multiply by 145.

[d] 50% rh = conditioned to 50% relative humidity at 23°C.

[e] To convert J/m to ft·lbf/in., divide by 53.38.

3. Mechanical Properties

The semicrystalline structure of most commercial nylons imparts a high strength (tensile, flexural, compressive, and shear) as a result of the crystallinity and good toughness (impact strength) due mainly to the amorphous region. The properties of nylon are affected by the type of nylon (including copolymerization), molecular weight, moisture content, temperature, and the presence of additives. Strength and modulus (stiffness) are increased by increasing density of amide groups and crystallinity in aliphatic nylons; impact strength and elongation, however, are decreased. Nylon-6 having a lower crystallinity than nylon-6,6 has a higher impact strength and slightly lower tensile strength. Nylons containing aromatic monomers tend to have increased stiffness and strength by virtue of the greater rigidity of the chains. Increasing molecular weight gives increased impact strength without having a significant effect on tensile strength. Moisture content affects the properties of nylon-6 and nylon-6,6; the effect is similar to that of temperature. Increasing moisture content reduces the T_{g} above which the modulus and tensile strength drop significantly; however, some polyamides with a high T_{g}, such as those containing aromatic monomers, have little change in properties with changing moisture as the T_{g} remains above room temperature. Increasing moisture for nylon-6 and nylon-6,6 also gives a steady increase in impact strength as a result of increasing plasticization, although at very low temperatures moisture can embrittle

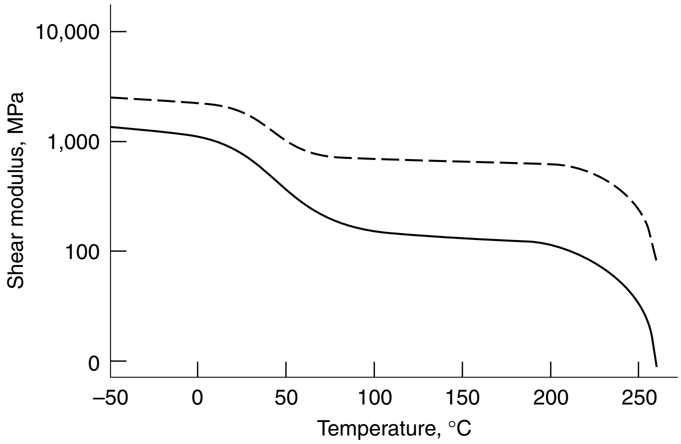

Fig. 2. Effect of temperature on the shear modulus of dry nylon-6,6 (—) and nylon-6,6 plus 30% glass fiber (– – –). To covert MPa to psi, multiply by 145.

nylon. For nylons that absorb lower amounts of water, the effects on properties are less.

The effect of temperature on properties can be seen in Figure 2, which shows the effect on modulus of increasing temperature of unmodified and glass-reinforced nylon-6,6. Impact strength, however, shows a steady increase with temperature as it does with moisture.

Generally, nylon is notch-sensitive and the unnotched impact strength is dramatically reduced when a notch or flaw is introduced into the material. This needs to be considered when designing parts so that sharp angles are avoided where possible. This notch sensitivity can be considerably reduced by incorporating impact modifiers. For the most effective of these materials, the notched impact strength approaches the unnotched impact performance of the unmodified resin. The increased ductility of the material that accompanies impact modification does, however, reduce stiffness and strength. Moisture conditioning of moldings is often used to increase impact strength and flexibility before such operations as snap fitting or assembling cable ties, which can be avoided in some cases by using impact-modified resins. The effect of impact modifier on the properties of nylon-6,6 is shown in Table 3.

Properties such as stiffness and strength can be considerably increased by adding a reinforcing agent to the polymer, particularly glass or carbon fiber. Inclusion of a filler or reinforcement forces the material to fail in a brittle rather than ductile fashion. As a result, the unnotched impact strength and elongation are reduced, although the notched impact strength may be increased. These materials maintain their mechanical integrity under a high load almost up to the melting point of the nylon, eg, deflection temperature under load (see Table 3). Mechanical properties can also be modified by the inclusion of plasticizers, which have a similar effect to that of water in breaking down hydrogen bonding in the amorphous region and increasing ductility, flexibility, and impact strength. Table 3 also shows the effect of glass and plasticizers on nylon-6,6 and nylon-12 properties, respectively.

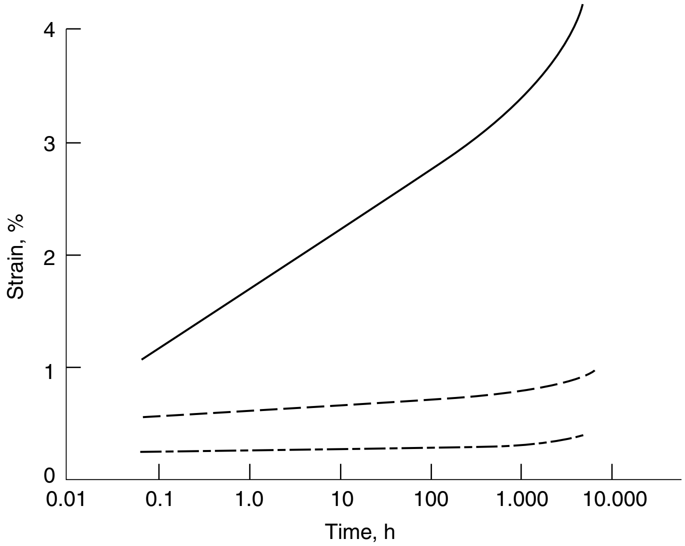

Fig. 3. Tensile creep of nylon-6,6 at 50% rh, 23°C, and 15 MPa (2175 psi) (—), reinforced by 15 wt% glass (– – –), and 33 wt% glass (– -).

As with most plastics the properties of nylons are time-dependent. The strain in a molding constantly under load increases with time (creep); equally, the load or stress required to maintain a constant deformation decays with time (stress relaxation). Some creep curves are given in Figure 3. Glass-fiber reinforcement considerably improves the creep performance. Nylons have good resistance to dynamic fatigue, ie, the application of cyclic loads. This is influenced both by the frequency and wave form imposed as well as by moisture, temperature, and the presence of notches. Again, glass-fiber reinforcement considerably improves the number of cycles that can be withstood. Nylon-6,6 has much better fatigue resistance than nylon-6, and it is claimed that nylon-4,6 is much better still (9). Nylon is also particularly resistant to damage from repeated impacts; much better, for example, than some metals that have a high impact resistance to a single blow.

Two more properties for which nylon shows particular advantages are abrasion resistance and coefficient of friction. These properties make the material suitable for use in, for example, unlubricated bearings and intermeshing gears; nylon has been used in such applications from an early stage in its development. Wear and friction properties can be further improved by use of appropriate additives; for example, abrasion resistance can be increased considerably by the use of aramid-fiber reinforcement and PTFE, graphite or molybdenum disulphide have been used to significantly reduce friction (and often also wear) in moving parts.

4. Chemical Properties

4.1. Hydrolysis and Polycondensation.

One of the key properties of polyamides relates to the chemical equilibrium set up when the material is polymerized. The polymerization of nylon is a reversible process and the material can either hydrolyze or polymerize further, depending on the conditions.

In the melt the material is in a dynamic situation and only at a certain (equilibrium) moisture content does the rate of hydrolysis equal the rate of polymerization. This equilibrium moisture content (in a sealed system) depends on the polymer, the temperature, the molecular weight, and the end group balance of the polymer. Below this moisture content, the melt increases in viscosity (polymerizes) and above it hydrolysis occurs with reduction in viscosity and molecular weight. For nylon-6,6, the equilibrium moisture content is close to 0.15% for most standard injection-molding resins; however, the figure is less for reinforced materials as less nylon is present per unit weight. For high molecular weight nylons used for extrusion applications, the equilibrium moisture content is less as the concentration of end groups is less; therefore, these materials need to be processed at lower moisture contents to avoid lowering the molecular weight. Nylons also polymerize in the solid form (solid-phase or solid-state polymerization) if heated significantly above 100°C in the absence of water. The equilibrium also means that nylons can hydrolyze when parts are exposed to aqueous environments for long periods at high temperatures, leading to loss of properties. However, this depends on the conditions of exposure. Nylon-6,6 has long been used successfully for automobile radiator end tanks and washing machine valves and has recently been used for pump housings for the boilers of domestic central heating systems (15). Nylons that absorb lower amounts of moisture have improved hydrolysis resistance, and semiaromatic nylons have been used for some higher temperature applications (16).

4.2. Thermal Degradation. Although nylons have good thermal stability, they tend to degrade in the melt when held for long periods of time or at high temperatures. This is particularly the case for nylons containing adipic acid such as nylon-6,6. The adipic acid segment can cyclize, leading to chain scission and the production of cyclopentanone and derivatives and evolution of carbon dioxide and ammonia. Alongwith reduction of molecular weight, crosslinking also occurs, and the material eventually sets into an intractable gel. This is normally not a problem with plastics processing operations where the residence time is relatively short, but loss of molecular weight during injection molding can occur as a result of this, particularly at high temperatures (over 300°C) or where the shot size is a small proportion of the machine capacity. Significant evolution of carbon dioxide also occurs. Processing machines should not be left containing molten nylon for any length of time but should be either emptied or purged out with, for example, a polyolefin.

4.3. Oxidation. All polyamides are susceptible to oxidation. This involves the initial formation of a free radical on the carbon alpha to the NH group, which reacts to form a peroxy radical with subsequent chain reactions leading to chain scission and yellowing. As soon as molten nylon is exposed to air it starts to discolor and continues to oxidize until it is cooled to below 60°C. It is important, therefore, to minimize the exposure of hot nylon to air to avoid discoloration or loss of molecular weight. Similarly, nylon parts exposed to high temperature in air lose their properties with time as a result of oxidation. This process can be minimized by using material containing stabilizer additives.

Improvements in recent years have allowed nylons to be used at higher temperatures without problems, and formulations to minimize yellowing with aging have been developed.

4.4. Ultraviolet Aging. Nylon parts exposed to sunlight and uv rays undergo a similar free-radical aging process. Again, this can be reduced with appropriately stabilized materials.

4.5. Effect of Chemicals and Solvents. Nylons have excellent resistance to many chemicals, although the effect varies depending on the nature of the nylon. Generally, polyamides tend to be particularly resistant to nonpolar materials such as hydrocarbons. Resistance is least to strong acids and phenols which are most effective at disrupting the hydrogen bonding and which can sometimes dissolve the nylon. Highly polar materials such as alcohols are absorbed and sometimes dissolve the nylons containing lower concentrations of amide groups. Ethylene glycol, which is used in engine coolants, is absorbed by polyamide and dissolves nylon-6,6 (and nylon-6) above 160°C. Certain metal salts can attack nylon causing stress cracking, eg, zinc or calcium chloride, or even dissolve the material in alcoholic solution, eg, lithium chloride.

5. Manufacture

5.1. Solid-State Polymerization. There is a limit to the molecular weight that can be obtained in a melt-polymerization process as a result of degradation with long melt residence times and limits to the diffusion rate of moisture out of high viscosity melts. In order to produce high molecular weight resins to be used in, for example, extrusion operations, it is necessary to polymerize further by heating in the solid state. This is carried out under vacuum, steam, or inert gas. Nylon-6,6, for example, can be solid-state-polymerized in the temperature range of 150–240°C. Below the melting point, the hydrolysis rate is negligible compared to the reaction time, and degradation reactions are also much reduced. This process can be carried out by a batch or continuous process. The batch process involves tumbling granules in a heated rotating vessel under vacuum or a stream of inert gas. The continuous process uses a column with heating and cooling sections, granules enter at the top and exit at the bottom against a counter current of inert gas, and the residence time is set to give the molecular weight increase required.

5.2. Compounding. Although low levels of additives such as lubricants can often be incorporated during the polymerization process (internally or surface coated onto granules), in order to add the required higher levels of, eg, glass-fiber reinforcement, impact modifiers, or flame retardants, it is necessary for the nylon to undergo a second manufacturing step to melt-incorporate the additives. This is carried out by extrusion compounding, which usually consists of a gravimetric feed of additives and nylon granules to a single- or twin-screw extruder. The screw conveys the mixture along a heated barrel and, by the action of shear on the polymer, melts the material and mixes in the ingredients. Twin-screw extruders usually have intermeshing co-rotating screws that are more effective at mixing the material than single-screws, and can be built up from modular components, allowing flexibility in selecting the average and localized shear/mixing regime along the screw. Additives such as glass fiber can be added along the barrel and into the melt in such designs; screw-side feeders can be used to do this. A vacuum line attached to a vent in the barrel allows the removal of moisture and volatiles. Material is extruded through a die into laces, which are water-cooled and pelletized. An alternative compounder is the co-kneader design which is a modification of a single-screw extruder but has axial motion as well as rotation and mixing pins engaging with the (modified) screw. This system allows a higher level of mixing to be achieved without generating excessive temperatures (particularly useful for temperature-sensitive additives) but requires a secondary crosshead or gear pump to develop pressure for lace extrusion (17).

5.3. Additives and Modifications. For plastics uses, nylon is only rarely employed as the pure polymer, and is almost always modified to some extent even if only with the addition of a small amount of lubricant. There has been a dramatic increase in the range and number of combinations of additives used to modify nylons, resulting in a huge expansion in the number of commercial grades available and the uses to which they can be put. It is not unusual to find formulations that contain less than 50% nylon and half a dozen or more additives.

Lubricants. Lubricants are used to improve the melt flow, screw feeding, and mold release of nylons. Long-chain acids, esters, and amides are used together with metal salts, eg, metal stearates. Improved melt flow is mainly a function of molecular weight reduction during molding. Mold release is improved by waxes of limited compatibility with nylon, which migrate to and lubricate the mold surface. High molecular weight silicones have also been used to improve flow and mold release of polyamide.

Nucleants. Although nylons crystallize quickly, it is often an advantage, particularly for small parts, to accelerate this process to reduce cycle time and increase productivity. Nylon-6, which crystallizes more slowly than nylon-6,6, particularly benefits from nucleation in unreinforced formulations. Nucleants are generally fine-particle-size solids or materials that crystallize as fine particles before the nylon. The materials, eg, finely dispersed silicas or talc, seed the molten nylon and result in a higher density of small uniformly sized spherulites; in nylon-6, the crystalline form is also changed. Nucleation increases tensile strength and stiffness but makes the material more brittle. Mold shrinkage is lower for nucleated resins.

Stabilizers. Stabilizers are often added to slow down the rate of oxidation and uv aging. Heat stabilizers can be organic antioxidants (such as hindered phenols or aromatic amines), hydroperoxide decomposers, or metal salts. The latter are most commonly used in the form of copper halide mixtures. This system, which has the side effect of discoloring the nylon, acts as a regenerative free-radical suppressor. Above about 120°C, the copper halide system is by far the most effective and allows the use of glass-reinforced nylon-6,6 in high temperature automotive underhood applications. Ultraviolet stabilizers can be free-radical acceptors, uv absorbers, or hindered amine light stabilizers. Commonly, mixtures are used to give optimal performance, eg, a uv absorber such as a benzotriazole (or recently triazine) compound, to harmlessly absorb much of the uv energy, combined with a hindered amine light stabilizer (plus optionally a hindered phenol) to suppress reactive free radicals (18). The most common uv stabilizer, however, continues to be finely dispersed carbon-black pigment.

Impact Modifiers. Notched impact strength and ductility can be improved with the incorporation of impact modifiers, which can also lower the brittle–ductile transition temperature and give much improved low temperature toughness. Impact modifiers are rubbers (often olefin copolymers) that are either modified or contain functional groups to make them more compatible with the nylon matrix. Dispersion of the rubber into small (micrometer size) particles is important in order to obtain effective toughening (19). Impact modifiers can be combined with other additives, such as glass fiber and minerals, in order to obtain a particular balance of stiffness and toughness. Modified acrylics, silicones, and polyurethanes have also been proposed as impact modifiers.

Flame Retardants. Flame retardants are added to nylon to eliminate burning drips and to obtain short self-extinguishing times. Halogenated organics, together with catalysts such as antimony trioxide, are commonly used to give free-radical suppression in the vapor phase, thus inhibiting the combustion process. Additives that have been used are brorninated polystyrene, decabromodiphenyl oxide, and chlorinated dodecahydrodimethanodibenzocyclooctene (Dechlorane plus). In Europe, red phosphorus is widely used. It is effective at much lower levels and promotes char formation as well as inhibiting combustion, but is a more hazardous raw material to handle and the compounds are not available in light colors. Concern about the possibility of dioxin formation from resins containing halogenated organics, particularly those containing phenoxy groups, has led to increasing interest in nonhalogen, nonphosphorus flame retardants. Melamine derivatives have been widely used in unreinforced compositions and products have been developed based on magnesium hydroxide, although the high levels needed result in very poor mechanical properties. Recently nonhalogen, nonred phosphorus glass-reinforced flame retardant materials have been reported (20).

Plasticizers. Plasticizers are used to increase the flexibility of nylon and improve impact strength. They are most commonly used in nylon-11 and nylon-12 for such applications as flexible fuel hoses for automobiles. Plasticizers for polyamide are often sulphonamides, although others such as long-chain diols have been used as well as the caprolactam monomer in unextracted nylon-6. The latter material has been used for applications such as fishing lines.

Reinforcement. Nylon is particularly suitable for reinforcement and the melt incorporation of short glass fibers has long been practiced, being developed around 1960 by ICI in England (21) and Fiberfil Inc. in the United States (22). The tensile strength of nylon-6,6 is increased by more than 2.5 times and stiffness by almost 4 times by adding 30% glass fiber. Glass fiber also improves dimensional stability, notched impact strength, temperature performance and long-term creep, and is normally used in the 15–60 wt% range. The glass fibers used need to be treated with a specific sizing to enable bonding with the nylon and dispersion in the melt; the size formulations are proprietary but often contain an aminosilane coupling agent and a polyurethane or acrylic binder. Special sizing compositions have been developed to improve the retention of properties of nylon-6,6 when exposed to hot engine coolant, and glass fibers further improved in this respect continue to be developed. The fibers are normally added as 3- or

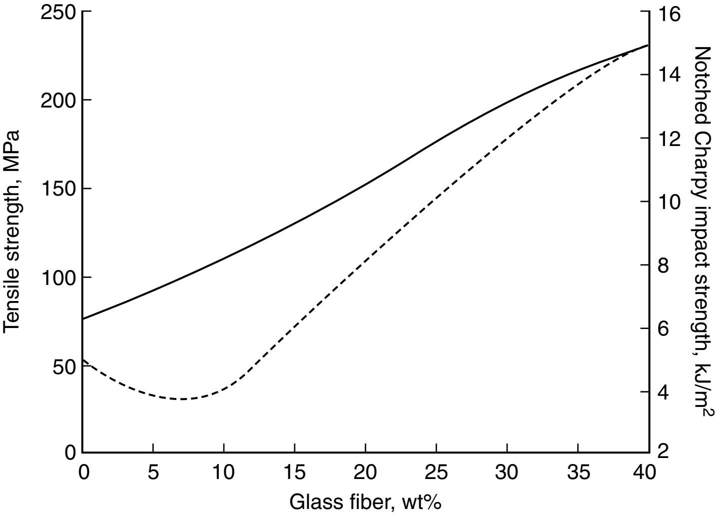

Fig. 4. Variation of tensile strength (——) and notched impact strength (- - -) with glass fiber level in nylon-6,6. To convert kj/m^2 to ft·lbf/in^2, divide by 2.10.

4.5-mm chopped strands (bunches of filaments), but the fiber length in the final product drops to a fraction of a millimeter after dispersion in the extruder. Figure 4 shows the relationship between glass fiber content and typical properties in nylon-6,6.

A disadvantage of glass fibers is the warpage of flat moldings. This is the result of differential shrinkage caused by anisotropy from the glass fibers, which tend to align with the direction of melt flow. Mineral reinforcements are used to obviate this by stiffening the material with a more isotropic mixture. Properties are lower than for glass fiber. Minerals having a higher aspect ratio, such as talc and mica, tend to have higher stiffness and strength; surface-treated kaolin and wollastonite have better impact properties. Combinations with glass are also used. Other reinforcements include mineral fibers, carbon fiber, and para-aramid fibers (Kevlar). Carbon fibers give very high stiffness but are much more expensive than glass; aramid fibers increase abrasion resistance.

Nanocomposites. These are materials in which nanometer size silicate layers are uniformly dispersed into polyamides to give high levels of reinforcement at very low levels (eg, 5%). The layer-type clay minerals are treated to make the layers separate allowing them to be incorporated into the polymer structure (intercalation). Initial developments involved incorporation during nylon polymerization but extrusion compounding routes have now been developed. Some advantages of this technology are low density and isotropic shrinkage (23).

Polymer Blends. Commercial blends of nylon with other polymers have also been produced in order to obtain a balance of the properties of the two materials or to reduce moisture uptake. Blends of nylon-6,6 with poly(phenylene oxide) have been most successful, but blends of nylon-6,6 and nylon-6 with polyethylene or polypropylene have also been introduced (24).

5.4. Pultrusion. A special variant of compounding is pultrusion, which is used in the manufacture of long fiber reinforced polyamide materials. In this technique, fibers (eg, glass fibers) are pulled through polymer melt usually with some mechanism to spread the fibers to allow complete wetting. On cutting the resulting lace, the glass fiber length becomes equal to the length of the granule. These materials can give high stiffness and impact strength combined with lower warpage (25) but need to be processed carefully (large gate size, low back pressure) to avoid reducing the glass fiber length to that of a standard short glass fiber product.

6. Processing

Nylons need to be processed dry to avoid molecular weight loss and processing problems. Figure 5 indicates both the usable moisture range for nylon-6,6 and nylon-6 in injection molding and the relationship with temperature (26). Extrusion applications require lower moisture contents (max 0.1–0.15% for nylon-6,6 and nylon-6) as do some other nylon types (eg, max 0.1% for nylon-11 and nylon-12; 0.05% for nylon-4,6). The materials are normally supplied dry by the manufacturer in moistureproof packaging such as foil-lined 25-kg bags or lined 1-ton boxes. Once opened, the material should be used within a few hours or resealed. Material that has absorbed some moisture can be redried using a vacuum oven at 80°C or a dehumidifier hopper drier.

Material should not be processed at too high a temperature, eg, preferably not above 310°C for nylon-6,6 or 290°C for nylon-6, in order to avoid degradation.

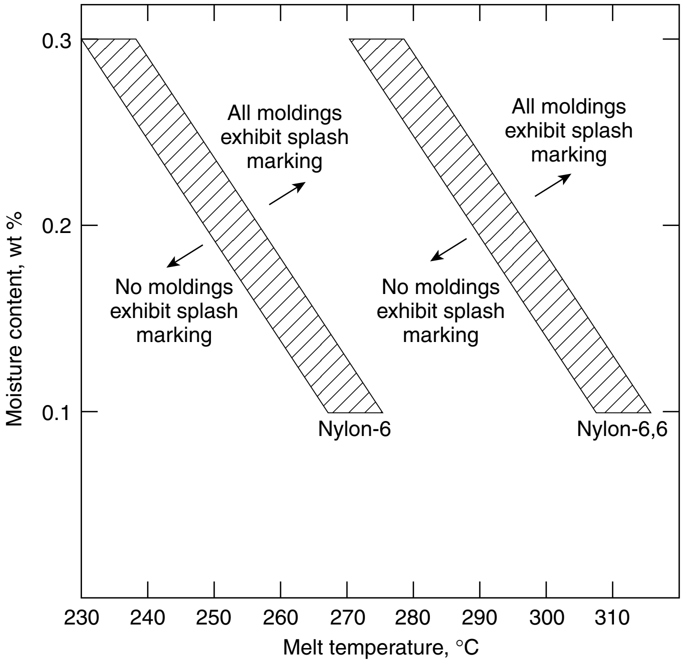

Fig. 5. Relationship between moisture content and temperature for an unvented cylinder during injection molding.

Residence times at the higher temperatures should be kept to a minimum. Molten nylon should not be left in an idle machine for more than 30 min maximum. Exposure of molten and hot nylon to air should also be minimized to avoid discoloration.

Generally, nylon scrap or regrind can be reused satisfactorily, provided that it is dry. The level allowed depends on the amount of degradation and the specification of the final products.

6.1. Injection Molding. This is the largest single processing route for nylon, taking more than 60% of the material produced. This technique is generally carried out using a screw preplasticizing injection-molding machine (27–29) (see Injection Molding). Nylons can often be processed on general-purpose screws having a constant decreasing flight depth along the screw, but better performance can be achieved by a nylon-type screw having a sharp reduction in flight depth within a few flights in the compression or transition zone. This allows for the sharp melting point of semicrystalline nylons, which results in a rapid reduction in bulk density.

The sharp melting point and the low melt viscosity also mean that nylon can give problems with nozzle drool and/or premature freeze-off. For this reason, it is normally necessary to use either a reverse-taper nozzle (fitted with a heater to avoid freeze-off), a mechanical shut-off nozzle, or melt decompression. The design of molds should also take into account this low viscosity and sharp melting point. Mold surfaces should be well-mated to avoid flash.

Table 4 gives injection-molding temperatures for various nylons. Typical molding conditions for polyamides are as follows: average injection velocity, 100–300 mm/s; hold pressure, 70–90 MPa; hold pressure time, 20–30 s; maximum injection pressure, 70–90 MPa; cooling time, ≤10 s; and total cycle time, ≤50 s. Nylons generally require a fast injection speed and are particularly good for achieving fast cycle times because of the low viscosity and rapid setting-up.

Significant mold shrinkage occurs with nylon, mainly on account of the increase in density with crystallization. This can give rise to voiding and sink

Table 4. **Injection-Molding Temperatures for Different Polyamides**[a]

Polyamide	Melt temperature, °C[b]	Mold temperature, °C
nylon-6	250–290	80
nylon-6,6	290–300	80–100[b]
nylon-4,6	315	120
nylon-6,9 and nylon-6,10	270	80
nylon-6,12	240–270	80
nylon-11	210–260	80
nylon-12	200–250	70–80[c]
nylon-MXD,6	250–280	130
nylon-NDT/INDT	280–300	80
polyphthalamide[d]	327–332	135–150

[a] Ref. 30.

[b] The higher temperatures are used for glass-filled or high viscosity materials and the lower temperatures for low viscosity or plasticised resins.

[c] The lower mold temperature is used if >5% plasticizer.

[d] Ref. 31.

marks in moldings. The dimensional stability can be much improved by using reinforcing agents or nucleated materials.

Developments in injection molding that have become increasingly important include gas injection and fusible-core molding. Gas injection enables a saving in part weight and avoidance of sink marks in thick sections. This technique has recently been upgraded for use in tubing applications where the hollow core formed by the gas pushing out molten nylon from the center becomes the bore of the tube. Special materials are required to give a smooth internal surface. Fusible-core technology involves overmolding a low melting metal alloy core that is subsequently melted out in an oil bath. This technique allows much more complex moldings containing internal passageways to be produced. The method had become important for making automobile air inlet manifolds but is now being mainly overtaken in this application by vibration welded parts. Another very recent technique, which is really a development of gas injection, is water injection. In this process, water under high pressure replaces gas in ejecting molten nylon from the center of a part; the advantage is more efficient cooling, shorter cycle times, and the potential to produce larger diameter tubes (32).

6.2. Extrusion. Extrusion accounts for about 30% of nylon produced and is used in various processes (33). Nylons can be extruded on conventional equipment having the following characteristics. The extruder drive should be capable of continuous variation over a range of screw speeds. Nylon often requires a high torque at low screw speeds; typical power requirements would be a 7.5-kW motor for a 30-mm machine or 25-kW for a 60-mm one. A nylon screw is necessary and should not be cooled. Recommended compression ratios are between 3.5:1 and 4:1 for nylon-6,6 and nylon-6; between 3:1 and 3.5:1 for nylon-11 and nylon-12. The length-to-diameter ratio L/D should be greater than 15:1; at least 20:1 is recommended for nylon-6,6, and 25:1 for nylon-12.

Typical operating temperatures are shown in Table 5. Most extrusion operations require high viscosity (high molecular weight) nylon in order to give a high melt strength to maintain the shape of the extrudate. In the following sections, reference is made to three broad viscosity ranges that correspond to these approximate number-average molecular weights when nylon-6,6 is used: high viscosity nylon ($M_n = 30{,}000–40{,}000$), medium viscosity (20,000–30,000), and standard viscosity (15,000–18,000, as used for injection molding).

Film. Nylon film can be produced as either tubular or cast film. In tubular film, melt is extruded through a screen pack and a tubular die, and a bubble is

Table 5. **Typical Temperatures (°C) for Nylon Extrusion**

Location	Nylon-6,6[a]	Nylon-6[a]	Nylon-12[b]
screw			
feed zone	265–275	220–230	185–205
compression zone	275–285	235–250	190–215
metering zone	285–295	245–265	190–220
head	285–295	250–270	200–230
die	285–295	250–270	195–230

[a] Ref. 33.
[b] Ref. 34.

formed with air pressure. Total drawdown (extension of the melt) of the order of 10:1 to 20:1 is achieved. High viscosity nylon is required for this operation. A relatively stiff, hazy film is produced; nylon-6 has a lower haze level than nylon-6,6. Cast film is produced from medium viscosity nylon by extruding through a straight slot die and then rapidly quenching on highly polished rolls at a controlled temperature; speed of the rolls affects drawdown as above. Nylon film is also produced as coextruded multilayer structures mainly with olefin-type polymers. Nylon film has a low permeability to oxygen, nitrogen, and carbon dioxide, but a high permeability to water vapor (see Barrier Polymers).

Tubing and Pipe. Medium to high molecular weight polymers are used for tube extrusion. Small bore tube (up to 10 mm) can be extruded through a conventional die and cooled in an open water bath. Air is injected into the center of the tube, using a torpedo to prevent the extrudate from collapsing and to adjust the wall thickness. For tubing larger than 10 mm, a pressure sizing die is used and tube is drawn into the water bath through a series of sizing plates in the end of the bath, 25–50 mm away from the die. A drawdown of about 2:1 is usually used, but this depends on the molecular weight and line speed. High molecular weight nylons require less drawdown than the less stiff lower molecular weight materials. Similar methods are used for large diameter pipe, for which high viscosity material is normally used, particularly with high wall thicknesses. As this is a slow operation, melt temperatures are kept up to 30°C above the normal melt temperature.

Monofilament. Standard and medium viscosity nylons are used. Close control of diameter is important and a gear pump is used before the die (after filtering through a fine filter pack) to minimize pressure variations. The die hole diameter is normally 1.5–2 times the diameter of the undrawn filament. The filaments are drawn through a quench tank at approximately 40°C, separated and then drawn by passing through two sets of rolls (running at different speeds) separated by a heated chamber. The drawn filament is set by passing through a final heated conditioning chamber.

Rod and Profiles. Medium to high viscosity grades are used. Accurate temperature control is important. For rods of diameters greater than 3 mm, slow solidification is essential to avoid voids and cracks caused by nonuniform shrinkage. Two processes are used. For rods up to 150 mm, a forming box is used whereby nylon is extruded under pressure through a water-cooled cylindrical tube. The tube is isolated from the die by a nonmetallic gasket, the rod is pulled off at a constant rate by a haul-off. The second process, which can be used for more complex shapes, involves extruding the nylon into a series of interconnecting open-ended molds.

Wire and Cable Coating. Nylons are widely used for wire covering and sheathing cable. In the latter application, nylon is usually overcoated onto insulation of another material, such as PVC, in order to provide cut and abrasion resistance. In a specialized application, nylon-11 and nylon-12 are used to provide termite resistance. Amorphous polyamides have been used for sheathing of optical fiber cables.

6.3. Blow Molding. Blow Molding of nylons has become more important as a means of making large hollow moldings. In addition to high molecular weight nylon, resins modified to increase melt strength and containing glass fiber have been introduced, and impact modifiers are often used to increase melt elasticity. Blow molding of nylons is usually carried out by extrusion blow molding, whereby melt is produced in an extruder and formed into a tube called a parison (35). The molten parison is captured in a mold that pinches and seals the ends, and the rigid hollow part is formed by inflation under air pressure. Intermittent extrusion blow molding is most common, which involves the storing of melt in an accumulator die head until required to form the next parison, melt storage with a reciprocating screw or accumulator pot with ram is often used. Continuous blow molding and injection blow molding (for small parts) can also be used. The parison can also be inflated using suction blow molding and this technique is now becoming increasingly important. Suction blow molding is especially suitable for 3-D parts where the parison can be effectively pulled through complex mold shapes using vacuum. The design of the manifold and accumulator head should be such as to avoid material hold-up locations (giving degradation and gel formation), and should also incorporate even, carefully controlled heating. Adequate venting of the head is necessary to avoid buildup of gas.

6.4. Rotomolding.

Nylon-6, nylon-11, and nylon-12 can be used in rotomolding and are generally supplied for these applications as a powder or with a small pellet size. The process involves tumbling the resin in a heated mold to form large, thin-walled moldings. Nylon-11 and nylon-12 use mold temperatures of 230–280°C and nylon-6 is processed at over 300°C. An inert gas atmosphere is preferred to avoid oxidation.

6.5. Reaction Injection Molding.

RIM uses the anionic polymerization of nylon-6 to carry out polymerization in the mold. A commercial process involves the production of block copolymers of nylon-6 and a polyether by mixing molten caprolactam, catalyst, and polyether prepolymer, and reacting in a mold (36,37).

6.6. Powder Coating.

Nylon-11 and nylon-12 are used in powder form for anticorrosion coating of metals. Dip coating and electrostatic and flame spraying are used. Dip coating, which involves immersing a preheated article into fluidized nylon powder, is most suitable for automation.

6.7. Assembly Techniques.

After molding, parts produced in more than one component can be assembled by snap fit, bolting, rivetting, welding, or gluing. Welding has become much more widespread in the last 10 years, with vibration welding in particular finding use to produce complex parts such as automotive air intake manifolds in a more cost effective manner than the capital intensive lost core process. Ultrasonic welding is also used (requires the nylon parts to be dry) and recently both hot plate and laser welding (38) have attracted considerable interest. Special polyamide materials have been developed for both these latter techniques. Polyamide parts can also be glued together, aided by the high surface energies of these polymers. Joint strengths are however much lower than when welded. Certain epoxy and polyurethane glues can be used sucessfully with polyamides although epoxies may give better resistance to temperature. Nylon–nylon joints are stronger than, for example, nylon–aluminum.

7. Economic Aspects

The principal worldwide manufacturers of nylon resins are given in Table 6.

Total demand for nylon resins in the United States, Canada, Europe and East Asia reached 1.7 million metric tons valued at well over $5 billion in

Table 6. **Manufacturers of Polyamide Plastics**

Manufacturer	Nylon type	Trade name
United States		
E. I. du Pont de Nemours & Co., Inc.	6, 6, 6, 12, and others	Zytel and Minlon[a]
Ticona U.S.	6, 6	Celanese
Solutia	6, 6, 6, 9	Vydyne
Honeywell	6	Capron
BASF Corp.	6	Ultramid
EMS-American Grilon, Inc.	6	Grilon
Nylon Corp. of America	6	Nycoa
Atofina Chemicals, Inc.	11	Rilsan
BP Amoco	PPA	Amodel
France		
Atofina	11, 12	Rilsan
	Polyamide blends	Orgalloy
Rhodia	6, 6, 6, 10	Technyl
Germany		
BASF AG	6, 6, 6, 6, 10	Ultramid
Bayer AG	6	Durethan
DuPont de Nemours	6, 6	Zytel and Minlona[a]
Degussa-Hüls AG	12	Vestamid
	NDT/INDT	Trogamid
Italy		
Rhodia	6, 6, 6	Technyl
Radici Novacips SpA	6, 6,6	Radilon
Netherlands		
DSM	6, 6, 6	Akulon
	4, 6	Stanyl
Japan		
Asahi Chemical Industry Co., Ltd.	6, 6	Leona
Mitsubishi Engineering-Plastics Corp.	6, 6, 6	Novamid
	MXD,6	Reny
Mitsui Chemicals	66, 6T, 6T, 6I	Arlen
Toray Industries, Inc.	6, 6, 6, 12	Amilan
Ube Industries, Ltd.	6, 6, 6, 12	Ube Nylon
Unitika, Ltd.	6, 6, 6	Unitika
Switzerland		
EMS Chemie AG	6, 6, 6, copolymers	Grilon
	12, transparent amorphous	Grilamid
	Amorphous copolymers	Grivory
United Kingdom		
BIP Plastex Ltd.	6	Beetle
Israel		
Nilit	66	Polynil

[a] Mineral filled.

2003. This level of consumption reflects an average annual growth rate of about 2.6% over the three-year period from 2000 to 2003. Total consumption of nylon resins in these regions is forecast to increase to about 2.1 million metric tons by 2008, representing an average annual growth rate of about 5%. This growth is considerably less than in the recent past, but reasonably good growth was projected to resume in major markets such as automotive parts, industrial/ machinery and film in 2004. In North America, industry data for the first five months of 2004 did not support these growth projections as numbers were flat versus a similar period in 2003 (3).

8. Specifications, Standards, and Quality Control

Raw material specifications may be agreed between the supplier and the molder or end user, or they may be defined as requirements by an external body. The standards ASTM D4066 (39) and ISO 1874-1/2 identify how to classify and specify nylon materials and give details of tests and test methods that may be used, as well as required values. ASTM D5336 for polyphthalamides is also used. The tests include mechanical, thermal, electrical, and flammability properties as appropriate. In addition to these, it is normally necessary to specify the viscosity of the material, maximum moisture content, and ash content (if reinforced). Viscosity is generally measured as solution viscosity that corresponds directly to molecular weight, rather than melt viscosity, which is moisture-dependent. In the United States, solution viscosity is generally measured as relative viscosity (ASTM D789) or inherent viscosity (ASTM D2857), normally in 90% formic acid or *m*-cresol solvent. Elsewhere, viscosity measurements mainly use the internationally agreed viscosity number (ISO 307) in formic acid, sulfuric acid, or *m*-cresol. Moisture content is determined according to ASTM D789. The test employs a coulometric Karl Fischer titration technique using a nitrogen-flushed heated chamber to drive moisture into the solution. Commercial equipment is available to carry out this test. Manufacturer's quality control tests normally include tests for contamination, color, moisture, ash, viscosity, packaging (qv), and other properties as appropriate.

In recent years most polyamide suppliers have made data available using a common computer database software known as CAMPUS (Computer Aided Material Preselection by Uniform Standards). All data in this database is measured in common ISO format (ISO 10350 for single point and ISO 11403-1/2 for multipoint data) and allows easy data retrieval and comparison between grades and suppliers. The CAMPUS internet site (http://www.campusplastics.com/) contains a listing of the participating companies and in many cases gives links to where their data can be downloaded.

9. Recycling

The issue of the recycling of polyamide parts has become a hotly debated issue since the second half of the 1990s. In the light of expected future legislation, a number of pilot schemes have been started to investigate collecting and recycling parts such as automotive components. The most advanced schemes however concentrate on reusing nylon carpets in plastic end uses. These processes are complex and expensive as considerable pretreatment of the post-consumer article is required before it can be reused in a plastics compounding process. The product can be recompounded directly (mechanical recycling) which invariably leads to a lower quality resin as contamination and/or unwanted ingredients cannot be entirely removed. The route to highest quality resin is achieved by chemical recycling in which the polyamide is taken back to monomer, purified, and repolymerized. A plant to chemically recycle nylon-6 had been started in the United States in 1999 (40) and a demonstration plant to recycle nylon-6,6 (as well as mixtures with nylon-6) was commissioned in 2001 (41). The final development of recycling will probably involve a balance of part reuse, energy recovery, mechanical recycling, and chemical recycling. Work is underway to broaden the range of materials recycled (3).

10. Applications

Descriptions of uses for polyamides, split into the principal application areas are given below.

10.1. Automotive. Not only is this the biggest single application area for polyamides but the rapid increase in the number of new applications is strongly influencing the overall growth rates for the polymer type. Metal replacement is being driven by both weight savings (and therefore fuel efficiency) and lower manufacturing costs.

Underhood. Polyamides have been used under the hood for a long time and applications such as radiator end tanks, filter housings, connectors and cable ties, together with nylon-11 and nylon-12 for fuel hoses have been long established. Certain applications such as filter housings may have mainly switched to lower cost polymers such as polypropylene but this has been far more than balanced by a huge growth in new uses. During the 1990s nylon air intake manifolds had essentially replaced aluminum and use of polyamides had extended to fuel rails, fans, fan shrouds, thermostat housings, and valve and engine covers. Some of the latest developments are front end modules (often nylon/metal hybrid structures) (42) and water tubes or water rails to replace rubber hoses in the coolant circuit. These tubing parts can potentially be made by either gas injection molding or blow molding, depending on the complexity and functionality required.

Interior. Again, polyamides have been used for some time for switches, handles, seat belt components, etc. Big new applications include air bag containers (very tough stiff resins are required to withstand the explosive inflation forces), pedals, and pedal boxes. Polyamides have also been used to replace metals in seat systems (42).

Exterior. Probably the biggest exterior application for polyamides is for wheel covers where mineral reinforced compositions are used to get the required degree of dimensional stability and flatness. Moves to use lower cost polymers have had limited success so far because of the better resistance of nylon to temperatures developed during braking. Other exterior applications include sun roof surrounds, door handles, fuel filler flaps, etc. One special application is the use of a nylon product (DuPont Selar®) as a fuel barrier material in polyethylene fuel tanks.

10.2. Electrical/Electronic. The electrical insulating properties of polyamides together with temperature performance, toughness, and inherent low flammability have long driven use in electrical and electronic applications. Uses include cable ties, connectors, light housings, plugs, and switches. Flame-retardant materials are also used for switchgear, housings, relays, circuit breaker components, and terminal strips. The advent of higher melting, higher heat-distortion temperature polyamides has allowed more temperature sensitive applications to convert to plastics. A new area for these types of products is for printed circuit boards using surface mount technology for which resistance to soldering temperatures is necessary. One additional application area is for housings for electronic equipment using products modified to provide an electromagnetic barrier and static dissipation.

10.3. Consumer. Polyamides are used in a number of consumer applications. A long-standing use is for power tool housings made from glass-reinforced nylon-6 or nylon-6,6 often containing impact modifier. A variation of this is a chain saw handle made using gas injection to reduce the weight; nylon monofilament is also used for strimmer cord. Sports equipment is one area in which polyamide use has expanded significantly and nylon has been used in ski boots and ski bindings, ice or roller skates, sports shoe soles, and tennis rackets (using carbon fiber reinforcement). Other miscellaneous applications include lighters, kitchen utensils, toothbrush filaments (nylon-6,12), chair bases and arms, spectacle frames, sewing thread, and packaging film (including cook-in-the-bag envelopes).

10.4. Industrial. This covers a huge range of unrelated areas of use. Nylon has been used from the early days in various gears and pulleys as well as in bearings and bearing cages, fasteners, and valves. Low melting nylon terpolymers are used as hot melt adhesives, nylon-12 for wire coating (including dish washer baskets), and amorphous nylons are used for transparent filter bowls and flow meters and for protecting optical fiber cables. Other uses have been stadium seats, sliding rails for conveyors, washing machine valves, castors, rail insulator pads, fishing lines, window thermal insulation, and film for medical applications. Some recent applications are pump housings for central heating systems (15), an all-nylon shopping trolley (43) and a substitute for wood beams, planks and boards (44).

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