Testing

TESTING AND STANDARDS

The word test means an examination performed to evaluate performance or capability of a material, a compound, a test piece or a component. A test may be performed on a raw material (in powder or granular form), a piece specifically made for testing, or a formed part.

Reasons for Testing

Testing is often time consuming and expensive, so, before considering specific tests, the purpose or object of the testing in general has to be decided. Testing is nothing new. Over the years, many tests have been devised to enable judgements to be made on the:

• Quality and consistency of raw materials
• Quality and consistency of associated products
• Merits of new or modified materials
• Suitability of a particular design

The need to carry out adequate fitness-for-purpose, and quality control testing, has increased greatly in recent years as a result of legislation on liability for product performance. New legislation is making the risk of punitive damage claims for product liability a very real possibility that manufacturers and suppliers must face and guard against. They must ensure that their materials and products are not in any way defective.

Standards Organizations

Tests are performed as specified by a test standards (Table 3.) which are issued by national or international standards organization (see separate Appendix). An example of a national standards organization is the American Society for Testing of Materials (ASTM). The International Standards Organization (ISO) is an international organization. It should be noted that the same answers may not automatically be obtained if a material/test piece is tested by one standard and then by another, for example, by an American Society for Testing and Materials (ASTM) method and then by an ISO method. Differences in the reported values are not necessarily due to changes in the material, but may be due to differences in test piece preparation, dimensions, conditioning or to changes in the actual test method used.

Factors Influencing Test Results

There are a large number of factors that will influence the results obtained from a test such as test machine design, test piece size, shape and method of production, conditioning of the samples, temperature during the test, etc. Standardization of test methods is essential, if people in the same laboratory or in different laboratories, are to obtain the same result on the same material. Since there are a large number of factors that will influence the results obtained, it is obvious that standardization of test methods is essential. Standard test sample conditioning must be employed. Often this conditioning

is simply storing the specimens at a standard temperature, for a specified time, before testing. Despite its simplicity, such physical aging is important as post-molding changes commonly occur. For many materials, such as some engineering thermoplastics, the specimens should be stored for a specified time under conditions of specified humidity.

Test Results and SI

Most test results are measured and quoted in the units specified by the Système International d'Unité (SI). The formal content of SI is determined and authorized by the General Conference of Weights and Measures. The units issued by the SI are a coherent international system of units now widely used for scientific and technical work. As there is coherence between units, this removes awkward factors in calculations involving quantitative relations. The seven basic units are the meter (length), kilogram (mass), second (time), ampere (electric current), degrees Kelvin (temperature), mole (amount of substance) and the candela (luminous intensity). There are supplementary units for plane angle (radian) and solid angle (steradian) and some SI derived units that have special symbols. These SI derived units that have special symbols include the Newton and the Pascal. Certain other non-SI units are permitted, for example, cm and ˚C. SI units were derived from the MKS system and are sometimes occasionally known as MKSA metric.

Families of Materials

Each of the many plastics and rubbers available is, in effect, a family of materials that differ in such factors as molecular weight and molecular weight distribution. What this means is that it is possible to get a wide range of properties for each of the materials groups. Properties quoted in the literature should, therefore, only be used as a general guideline as, for example, where the exact composition or structure of material tested is not known. The properties of plastics may also be dramatically changed by the processing conditions employed and by the use of additives. With many materials, variations of basic formulations are available using additives to provide for improved properties such as, heat resistance or, weatherability. Some formulations offer improved impact strength while others, which contain fillers, are used where the moldings require tensile strength or or higher heat distortion temperature. Processing and performance modifiers such as anti-static or nucleating agents may be added. These additives may form part of the color masterbatch.

Restriction of Testing

Most of the tests described here, although standardized, are usually only suitable for relatively simple purposes such as for checking the quality of a material being produced. Even so, such testing is expensive and it is therefore important to restrict it as much as possible. Unnecessary testing, on materials or products, should not be performed. (For example, the testing of gloss, or finish, on parts, which are to be hidden in service, would seem to be pointless.) Before a test is performed it must always be decided what will be done, with the results and with the components, after testing. It is very important that test specifications are drawn up at a very early stage in the production process. The use

of written specifications and procedures is vital. Once production has started, periodic reviews of the tests are essential to ensure that the test programs continue to provide what is required.

Table 3.
Standard Tests Used for Property Guidelines

	ASTM	ISO	BS	DIN	Other
Conditioning and Test Sample Preparation					
Cond. of materials		291	2782 Pt10		
Test piece preparation			2782 Pt9		
Cond. of test pieces			2782		
Density & Dimensions					
Density/rel. density	D 792	1183	2782 Pt6	53479	
Dimensions			2782 Pt6		
Apparent bulk density			2782 Pt6		
Bulk factor			2782 Pt6		
Short Term Mechanical Tests					
Tensile strength	D 638M	R527	2782 Pt3	53455/7	
Elongation at break	D 638M	R527	2782 Pt3	53455/7	
Tensile yield strength	D 638M	R527	2782 Pt3	53455/7	
Tensile modulus	D 638M	R527	2782 Pt3	53455/7	
Specific modulus	See Tensile strength and Density/rel. density				
Compressive strength	D 695	604	2782 Pt3	53454	
Compressive modulus	D 695	604	2782 Pt3	53454	
Flexural strength	D 790	178	2782 Pt3	53452	
Flexural modulus	D 790	178	2782 Pt3	53452	
Izod impact strength	D 256	180	2782 Pt3		
Charpy impact strength	D 256	179	2782 Pt3	53453	
Tensile impact strength	D 1822		2782 Pt3	53448	
FWIS D 3029 2782 Pt3					
Mechanical Surface Tests					
Abrasion resistance	D 1242				
Taber abrasion res.	D 1044	3537	2782 Pt3	52347	
Friction	D 1894		2782 Pt8		
Ball hardness		2039-1	2782 Pt3	53456	
Rockwell hardness	D 785	2039-2	2782 Pt3		
Shore hardness	D 2240	868	2782 Pt3	53505	
Scratch hardness					
Softness			2782 Pt3		

	ASTM	ISO	BS	DIN	Other
Thermal and Temperature Dependent Properties					
Thermal conductivity	C 177				
Coeff. of thermal exp.	E 228 or 831			53752	
Shrinkage - linear	D 955	294-4	2782 Pt9		
Specific heat	C 351				
Glass trans. temp Tg	D 3418				
Melting point - Tm	D 3418	3148	2782 Pt1		
Softening point			2782 Pt1		
Vicat softening temp	D 1525	306	2782 Pt1	53460	
HDT 1.82 MPa/264 psi	D 648	75	2782 Pt1	53461	
HDT 0.45 MPa/66 psi	D 648	75	2782 Pt1	53461	
Relative temperature index				UL 746B	
Cold flex 2782 Pt1					
MFR/MFI	D 1238	1133	2782 Pt7	53735	JIS K7210
Melt viscosity				54811	
Flammability and Smoke Testing					
Vertical testing	D 635		2782 Pt1		UL94V/CSA
C22.2					
Glow wire		6458			IEC 695-2-1
Needle flame		6458			IEC 695-2-2
Limiting oxygen index	D 2863	4589	2782 Pt1		
Smoke testing	D 2843				
Permanence Tests					
Water abs. in 24 h	D 570	62	2782 Pt4		
Saturation water abs	D 570	62	2782 Pt4		
Chemical resistance	D 543		2782 Pt8		
ESC		4600	2782 Pt8		IEC 538A
Ageing	G 26/G 53				
Electrical properties					
Volume resistivity	D 257	6233			IEC 93
Surface resistivity	D 257	6233			IEC 93
Relative permittivity	D 150	2067/4542			IEC 250
Dissipation factor	D 150	2067/4542			IEC 250
Dielectric strength	D 149	2918			IEC 243-1
Arc resistance	D 495				
CTI		5901			IEC 112

	ASTM	ISO	BS	DIN	Other
Optical Properties					
Refractive index	D 542		2782 Pt5	53491	
Haze	D 1003		2782 Pt5		
Gloss	D 523		2782 Pt5	67530	
Long Term Mechanical Properties					
Creep	D 2990			53444	
Fatigue	D 671				

MATERIAL INSPECTION

Most thermoplastic materials are supplied as granules or pellets in bags, sacks, or bulk containers. When supplied in 50 lb/22.6 kg sacks, the material is often supplied in 20 bag (1,000 lb) loads. If supplied in 25 kg/55 lb bags then, the material is often supplied in 1,000 kg/2240 lb lots. Considerable discounts may be obtained if the plastic material is purchased in bulk and supplied in bulk containers. With some materials, this form of supply may not be acceptable in such cases as when excessive water absorption may occur.

Preliminary Inspection

Most plastic materials are accepted as being satisfactory until something goes wrong during a processing operation. It makes sense, however, to inspect the material before processing for color, particle size, particle size consistency and any obvious contamination. There is no point in processing 'outof spec' material as 'out-of spec' products will be the result. This applies particularly to recycled material. The feed to many extrusion processes is a mixture of virgin and regrind or recycled material. A major problem with recycled or reclaimed material is contamination (which may take the form of discolored material and/or fines). Therefore, a sample of the material should be inspected under a consistent light source for color and contamination and the regrind should be sieved to check the concentration of fines. Only that material with a specified concentration of fines should be used. The moisture content of the material should be checked and the material dried if necessary. Blend the dried, reclaimed material with virgin material in a precisely agreed to ratio and check appropriate properties (for example, flow rate and color) before the material is certified as being good enough for processing. If there is any uncertainty in regard to the quality of the material being fed to the machine, then it should not be used.

Moisture Absorption

Moisture absorption is a measure of how much water (moisture) a component, or material, will absorb under specified conditions and over a certain time. Many plastic materials absorb water (that is, they are hygroscopic). This absorbed water changes dimensions and properties including electrical insulation, dielectric properties, mechanical properties and surface appearance. The melt flow will also be affected. In general, the level of water/moisture in the material fed to melt processing equipment must be kept

very low as its presence in many polymers may lead not only to problems with processing, but also to post-extrusion problems and to chemical degradation. For instance with PC, the moisture causes chemical degradation that is detrimental to the performance of the finished product (impact strength is affected). The maximum permissible limit for moisture in the granules for production of good extrudates varies from polymer to polymer but, in general, should be kept below 0.1% as measured by the water absorption in 24 hours.

Water Absorption in 24 Hours (24 h)

Test pieces are generally molded discs 2 inches/50.8 mm in diameter and 0.32 mm thick. Three test pieces are used. Each test piece is conditioned by being heated at 50˚C/122˚F for 24 hrs. The test pieces are cooled, in a desiccator, and weighed. The test pieces are then immersed in distilled water at a specified temperature and for a specified time. For example, the test pieces are placed in a container with water at 23˚C/73˚C: after 24 h the test pieces are wiped dry and weighed. The change in weight is usually expressed as a percentage of the original weight, for example, 0.1%. Such a test gives the 24 hr. water absorption at room temperature. In general, if the 24 hr. water absorption is greater than 0.2% then, for injection molding, drying is usually necessary. For extrusion-based processes, the level is approximately 0.1%. An accelerated water absorption test may be performed by immersing the weighed, dried, test pieces in boiling water for 30 minutes, cooling for 15 minutes at 23˚C/73˚F and re-weighing.

Saturation Water Absorption

A saturation water absorption value is also quoted for many materials. This value is obtained by immersing the weighed and dried test pieces in water at 23˚C/73˚F until there is no further increase in weight upon re-weighing. For some materials such as nylon 6, that have a very high water absorption, graphs are published by the material manufacturers that indicate how the water content varies with humidity. This may be referred to as an equilibrium water content.

Measuring Moisture Content

Methods of measuring of the moisture content in a thermoplastic material include drying to constant weight and the Karl Fischer method. The Karl Fischer method, however, is time consuming, involves the use of pyridine (an unpleasant smelling liquid) and requires considerable technical skill. Drying to constant weight is also time consuming and often not satisfactory where very low levels of moisture need to be measured. Consequently proprietary instruments, which require little skill and which give a direct reading of moisture content in less than 30 minutes have been developed. An example is the OmniMark moisture analyzer. A separate weighing facility as well as the instrument is required. Ideally such an instrument should be sited close to the processing operation, rather than in a remote quality control laboratory, so that the moisture content of the material being processed may be readily checked. See **Table 4**. below for recommended moisture limits for extrusion processes.

Table 4.
Moisture Content Limits for Extrusion

Material	Moisture Content Limit %
Acrylic	0.05
Acrylonitrile-butadiene-styrene *	0.02
Cellulosics	0.40
Nylon 6 and 66	0.25
Nylon 11 and Nylon 12	0.01 - 0.10
Polycarbonate	0.02
Polystyrene	0.10
Polyvinyl chloride	0.08
Styrene-acrylonitrile	0.10
Thermoplastic polyester *	0.01

DENSITY AND DIMENSIONS

Most tests involve the measurement of one or more dimensions. The density of a material is of importance since materials are usually bought by weight and sold by volume. Apparent density measurements may be performed on material before an extrusion operation, as a quality control check. Melt density can be measured during a melt flow rate test (See Method A to B Conversion in Flow Rate Testing).

Units of Density and Specific Gravity

Density is defined as mass per unit volume. When expressed in grams per cubic centimeter (g/cc) it is numerically equal to relative density (specific gravity or SG). It is often given in kg/m3 (kilogram per cubic meter) although grams per cubic centimeter is more common (g/cm3 is the same as g/cc and gcm-3). It is suggested, for ease of understanding that when density is discussed, the units used should be Mg/m3 rather than kg/m3. This gives values that have the same numerical values as the well established g/cm3 values or SG values. 1 Mg/m3 = 1 g/cm3 = 1,000 kg/m3. Relative density is more usually referred to as specific gravity (SG). Relative density (rd or RD) is the ratio of the mass of a substance to the mass of an equal volume of water, at a specified temperature. Specific gravity or relative density has no units, as it is a ratio.

Density of Filled Materials

The densities of most commercial thermoplastics are low since they are generally based on carbon and hydrogen. Addition of inorganic fillers and fibers usually increases the density of the polymer blends since these materials usually have a density greater than that of the polymer. To calculate the density of a polymer composition, divide the total mass of the polymer composition by ,the total volume. For example, if 100 g of unsaturated polyester resin (UP) of density 1.28 g/cc is mixed with 50 g of glass filler (density 2.55 g/cc) then the

Compound Density =
100g + 50g / [100g/1.28g/cc + 50g/2.55g/cc] = 1.52 g/cc. (Eqn. 8)
This equation assumes that all the air spaces, or voids, in the mixture are filled.

Measurement of Density and Specific Gravity

Relative density (RD), more commonly known as specific gravity (SG), may be obtained by dividing the weight of a sample in air by the difference between the weight in air and the weight in water. Special balances (such as the L'homme and Argy) are available for direct measurement of relative density (RD or SG) based on this principle. A measurement of RD can be used to determine if opaque test pieces contain voids. If an accurate measurement of density is required, then this may be obtained from a flotation method. For example, the density of polyethylene (PE) may be obtained by the use of a water/alcohol mixture. Small pieces of the PE are placed in a beaker which contains a water/alcohol mixture with a density of approximately 0.9 gcm-3 (obtained by mixing 35 ml of methanol with 25 ml of distilled water at 23˚C). Additional water is then slowly added to the beaker. When the density of the liquid is the same as the density of the PE, then the pieces of PE will remain suspended. It is important to add the additional water slowly and to keep the solution well stirred. These precautions ensure that the liquid density is uniform and that the heat of mixing does not cause the temperature to rise to an unacceptable level. The density of the water/alcohol mixture may then be determined by a weighing bottle technique. A density gradient column may also be used for measuring density. The density of such a column gradually changes from top to bottom, so a small piece of a material dropped into it will come to rest at the point where its density matches that of the column. Glass floats of known density are used to calibrate the column. Some liquid mixtures used in such a column include water and ethanol (density range 0.8 to 1.0), ethanol and carbon tetrachloride (density range 0.8 to 1.6), water and calcium nitrate (density range 1.0 to 1.6) and, carbon tetrachloride and bromoform (density range 1.6 to 2.9). For foamed plastics, one can weigh a known volume of the material. In this case, a cube of the material is cut and weighed: the density is weight over volume.

Melt Density

Sometimes a measure of melt density is required. This is most easily measured on an apparatus used for measuring Melt Flow Rate by what is called Method B. Method B uses an electronic method to sense the plunger displacement and thus the volume of polymer displaced. Some machines can calculate the flow data from such measurements at the same time. (See Flow Rate) It should be noted that, for polymers, the melt density is always lower than the solid density.

Dimensions

Many tests require that the dimensions of the test piece are known and are known very accurately. The measurement of dimensions, such as length, width, and thickness of rigid materials is relatively easy to do and may be done with a simple external micrometer. Spring-loaded dial gauges are commonly used for soft or flexible materials and electronic non-contacting gauges are also available.

Gravimetric thickness is sometimes used, for example, to measure the thickness of an embossed component. This is a method of obtaining the thickness of a component from a determination of dimensions, mass and relative density. The gravimetric thickness in millimeters (mm) equals 10.0 W/A x RD: where A is the area, W is the mass and RD is the relative density. The gravimetric thickness in inches (in.) equals 0.394 W/A x RD: where A is the area, W is the mass and RD is the relative density.

TENSILE STRENGTH

Tensile testing is a very widely used test as it is relatively easy to perform, gives reasonably reproducible results and yields a great deal of information. From this one test one can obtain not only tensile strength, but also elongation and modulus. The same basic machine may also be used to perform a number of other tests (for instance, flexural strength and compressive strength) with relatively simple modifications.

Description of the Test

The tensile test machine is constructed so that as the test specimen is deformed at a pre-selected speed the resistance to deformation and the amount of extension are measured. In order to ensure that breaking does not occur at the grips, used to hold the test sample, the sample is usually dumbbell shaped. If a cut sample is used (for example, cut from sheet) then the surface finish of the cut edges must be controlled so as to minimize errors. The sample dimensions in the waist region (gauge section) are measured with a micrometer or dial gauge and then the sample is firmly gripped in the jaws of the machine. An extensiometer may then be clipped to the sample. One jaw of the machine is drawn away from the other (usually by an electric motor) at the specified speed. A load cell that is connected to one of the jaws, measures the resistance to deformation. A load/extension curve is usually produced automatically by the machine. Five specimens are normally tested and the average result(s) quoted together with the standard deviation.

Stress and Strain

The application of the tensile stress causes the specimen to stretch from its original gauge length (lo) to a longer length (ll). Tensile strain (Σ1), commonly referred to as strain, may then be defined as the change in length/original length which is

$\qquad$ Σ1 = (ll - lo)/(lo) (Eqn. 9)

Percentage strain = strain x 100.

If sufficient stress is applied then the sample will break. The percentage elongation at break (ΣB) is usually expressed as a percentage of the original length and this, therefore, may be expressed as longer length (ll) minus original gauge length (lo) divided by original gauge length (Io) times 100. Tensile strength at break, also called the ultimate tensile stress, may be obtained by dividing the force necessary to cause failure during a tensile test, by the cross-sectional area at break. As this area is difficult to measure, the tensile strength that is commonly quoted is that given by F/Ao. Where F is the force which causes failure and Ao the original cross-sectional area. Yield strength may be calculated

from the force at which the specimen continues to elongate without additional load. The stress and strain obtained by using the original sample dimensions are sometimes referred to as 'nominal' or 'engineering' stress and/or strain.

Young's Modulus

The ratio of stress/strain, when stress is proportional to strain, is called the elastic modulus or the Young's Modulus. It is a tensile modulus, obtained from the results of a tensile strength test. This value is commonly quoted for many materials as it gives an appreciation of the stiffness of a particular material. For materials such as steel the value of Young's Modulus, obtained from the slope of a stress/ strain plot (up to the yield point), does not depend markedly on the test conditions and has come to be regarded as a material constant. This is not the case for polymeric materials, since the results obtained depend markedly on the test conditions, for example, on the speed or temperature of testing. Young's Modulus, which is the elastic modulus for uniaxial extension, is the slope of the stress strain plot for small extensions: that is, stress divided by strain. It has the units of force per unit area, for example, N/mm2 or psi. For small extensions, this elastic modulus is approximately the same as the compressive modulus.

Creep Testing

A short term test, such as a tensile test, is not capable of giving information which can be used in the design of a continuously stressed component in a particular environment. It is only really suitable for quality control purposes. On the other hand, a creep test will indicate that a small load applied for a long period, to a thermoplastic material, can cause a significant deformation. Tests, such as a tensile test, are referred to as single point tests while creep tests take into consideration the effects that changes in time, temperature and environmental conditions have on the deformational properties of polymers. Creep tests are performed by weight loading a plastic sample, maintained at a specified temperature. Periodic measurements of the extension are made, perhaps over several years. Often a dumbbell specimen is chosen that has a very long parallel section, so the small deformations, which result upon loading, can be measured accurately. The material is tested at a specific temperature by applying a weight (or stress) by means of a lever system. Since large loads may produce only small extensions, a very sensitive and accurate extensiometer is required. Sample conditioning is extremely important and may involve regulation of test temperature and/or humidity for several months to ensure that the specimens are in equilibrium with their surroundings. In the case of nylon 66, such storage will allow water take-up to occur as well as allowing post-molding crystallization to develop. The results of creep testing may be expressed in various ways, for example, a creep modulus may be obtained by dividing the applied stress by the time dependent strain. If the creep modulus is divided by the room temperature elastic modulus (the Young's Modulus) then a reduced stiffness value is obtained. Creep modulus/time curves are obtained by plotting creep modulus against log time. A family of tensile creep modulus curves, as a function of strain and log time, may be obtained.

FLEXURAL PROPERTIES

Flexural properties are measured to obtain a measure of stiffness or rigidity. This may be a more appropriate test than measuring tensile strength if the extrudate is to be deformed by bending during its service life.

Test Specimens

The specimens used for flexural or bending tests are simple rectangular bars the length of which must be at least 20 times the thickness. The width and thickness can vary, but the preferred dimensions are width 10 mm and thickness 4 mm. All samples should be conditioned at the test temperature and appropriate humidity for a standard time. As for tensile testing, at least five specimens should be tested and the arithmetic mean and standard deviation of the five individual results reported. Where there is anisotropy, five specimens should be tested in two directions at right angles.

Flexural Strength and Modulus

Flexural strength is the strength determined from the load and the test piece dimensions in a flexural test. Flexural strength is also known as breaking strength and is usually measured by applying a stress at the center of a rectangular bar which is supported at two other points. That is, three-point loading is applied in a bending test. During the test, the force applied and the resulting deflection are measured. The test is usually performed on a universal testing machine (as used for tensile strength tests). Bending the specimens in a three point bending jig (on which the span or distance between the two outer supports is set 15 to 17 times the thickness) gives a load/deflection curve or graph. From this curve flexural strength and modulus are determined.

Calculations

If the specimen is brittle and breaks at very low strain (less than 0.05) then, the breaking or flexural strength is calculated from

$\sigma B = (3\ FB\ L)/(2\ b\ h2)$ (Eqn. 10)

Where σB is the flexural strength, FB = load at break, L = span width, b and h are width and thickness of the specimen, respectively. If the sample does not break but simply bends then the stress measured when the sample deflection reaches 1.5 times the sample thickness is used. The breaking strain is often given the symbol γ and equals 6D h/L, where D is the deflection at mid-span. The elastic modulus in flexure, symbol E, can be calculated from

$E = [L/(4\ b\ h3\ )](F/Y)$ (Eqn. 11)

where F/Y is the slope of the initial linear load-deflection curve.

IMPACT STRENGTH

In the plastic industry the most common type of impact test is a pendulumtype
test (such as the Izod or the Charpy Test). However, this is not the case
for the extrusion industry where an impact test is required to assess the
behavior of products such as film, sheet and pipe.

Falling Weight Impact Strength

The falling weight impact strength (FWIS) is the energy that on average causes 50% of test specimens
to fail in a FWIS Test. This test is a very useful type of impact strength determination. It is usually per-
formed on actual products, or on samples cut from them. The test is performed by allowing a projectile
to fall on the piece to be tested. End-use service performance can, therefore, be easily simulated, as
the sample will fail, as in a real life situation, along the line of least resistance. There are two main types
of tests employed and these have been called the conventional falling weight and instrumented falling
weight tests.

Conventional FWIS Test

In this test, widely used for testing film, sheet and pipe, the sample is struck by a weight attached to a
hemispherical dart or "tup" that falls from a constant height. By testing a large number of specimens
the energy, which on average causes 50% of them to fail, is determined. When extruded film is tested
the BS method requires that 14 m (45 ft) of film be available and that the film width is 260 mm. At least
60 successive but not overlapping test portions are obtained. It is usual to leave the film in the form of a
strip. A vacuum is used to clamp the film taut and then a dart is dropped on it from a specified height. If
the film is punctured then this is recorded as a failure and the procedure is repeated for a range of dart
masses. Sets of ten test pieces are used with at least six different dart masses. The percentage of
failures for each dart mass is recorded. The results are quoted as an M50 value. This figure is the mass,
in grams, of the dart that would be expected to break 50% of a large number of specimens. For sheet
the F50 value is quoted. This figure is the energy of the striker which caused 50% failure, that is, the
mass of dart (kg) x acceleration due to gravity (m-2) x height of fall (m). In this case the result is given
in Joules (J). A graph is drawn on probability paper of dart mass against the percentage of test pieces
punctured for each set of ten test pieces. The best fit straight line is drawn through the points and the
M50 value read off. This is reported as the falling weight impact strength of the film.

Instrumented Falling Weight

In this test a dart, or tup, is used which is so heavy that it will break the specimen easily, without a
significant decrease in striker speed. A transducer is mounted behind the nose of the striker and the
information that this generates is used to measure the maximum force and to calculate the energy to
break the specimen. Only a relatively small number of components or test specimens are required for
this test.

The test is normally performed at room temperature and the signal from the transducer, as it breaks the sample, is amplified, recorded and/or displayed. To get more consistent results, and to stop the sample wrapping around the nose of the tup, a striker with a flat face is sometimes used. The speed of the tup is measured photo-electrically. It is relatively easy to perform this test with only a few specimens over a range of temperatures to obtain information about ductile to brittle transitions. To show the effect of processing on properties, the results obtained by testing the actual components may be compared against results obtained when compression molded specimens of the same thickness, are used. Compression molded samples are assumed to be free of orientation, that is, isotropic. It has been found that a reasonably good approximation of the energy causing breakage (E*) can be obtained by multiplying the impact speed (V0) by the area under the force-time graph up to the point where failure begins, if the speed of impact (V0) remains virtually unchanged during the impact. That is:

E* = V0 fdt (Eqn. 12)

If the dart speed changes during the time it is forcing its way through the specimen, then a correction must be applied to E*. The corrected value of the energy of breakage (E) is then calculated from:

E = E* (1- E*/4E0) (Eqn. 13)

where E0 is the kinetic energy of the dart at the moment of impact.

HARDNESS AND SOFTNESS

The hardness and/or softness of a material commonly means resistance to indentation or penetration by a blunt indenter (a probe or a ball) loaded with a spring. Both the indenter and the spring have precisely fixed characteristics, since indentation is dependent on the indenter profile. The loaded indenter remains in contact with the test material and the depth of penetration is measured after a fixed time. Such a test is typically used for rubbers and plastics where rapid recovery, after removal of the deforming force, makes it impossible to measure the dimensions of the indentation.

Rockwell Hardness

The Rockwell Hardness is a number that indicates the hardness of a material as measured by an indentation test. The use of different loads and procedures gives several Rockwell hardness scales. Scale C is used for metals. Those used for plastics include R, L and M. Two procedures are used. The first when there is no appreciable recovery when the indenting force is removed and the second gives α Rockwell hardness values when there is recovery. For the first procedure, the test specimen is placed on a flat anvil below the indenter, and a minor load of 10 kg is applied, forcing the indenter into the material. Within 10 seconds the scale is set to zero. A major load of 60 kg, or 100 kg depending on the scale, is applied for 15 seconds and then immediately removed, with the minor load remaining. The hardness reading is taken from the scale 15 seconds after removing the major load. The second method is used with the R scale only and gives α Rockwell values. The indentation is noted 15 seconds after application of the major load, with the major load still applied. The α Rockwell hardness value is then obtained by subtracting the indentation from 150.

Shore Hardness

The Shore Hardness is a measure of the hardness or softness of a material as assessed by the resistance (on a scale of 0 to 100) experienced by an indenter. 100 on the scale corresponds to a high resistance (that given by a sheet of glass) and 0 corresponds to zero resistance. Two different indenters are used: Type A for soft materials and Type D for hard materials. This means that there are two scales of Shore Hardness, Shore A and Shore D. Type A measurements are made on soft materials using a truncated 35˚ cone with a blunt tip of 0.79 mm diameter as an indenter. Type D measurements are made on harder materials with a 30˚ steel cone rounded to 0.1 mm radius tip as an indenter. The depth of penetration is inversely indicated in thousandths of an inch. The harder the surface the higher the reading. The specimen must be conditioned prior to testing and it has to be sufficiently flat over an area of at least 6 mm/0.25" radius from the indenter point to allow contact with the foot of the instrument. It must also have a thickness of at least 6 mm unless it is known that identical results can be obtained with a thinner specimen. Measurements are made at several points over the surface simply by pressing the instrument against the surface of the specimen. Readings should be taken after a standard period of time, the ISO recommends 15 seconds and the ASTM one second.

Softness

The softness number gives a measure of softness. It is a measure of the resistance to indentation of a polymeric material, such as plasticized polyvinyl chloride (PPVC) compound. An indentor is pressed into a sheet of the PPVC compound under a specified load and the depth of penetration of the indenter is measured. The British Standard softness number is a number that indicates the softness of a material. The higher the number the softer the material. An abbreviation used for this term is BS Softness Number. A flat sheet or disc is used which is between 8 and 10 mm thick, conditioned at the test temperature and humidity. The time and temperature of conditioning is important. For example, it is recommended that temperature conditioning be seven days at 23˚C for plasticized polyvinyl chloride (PPVC) compounds. This is because the properties of such compounds are known to change over several days after molding. The test is performed using a duro-meter. This measures the increase in depth of penetration of a steel ball, 2.5 mm in diameter, into the flexible material, when the force on the ball is increased from 0.30 N to 5.70 N. The minor or contact load of 0.30 N is applied for 5 seconds and then the load is increased to 5.7 N. The reading on the dial is noted when 5.7 N has been applied for 30 seconds. Four readings are taken at different points on the surface, away from the edge of the specimen, and the average is expressed as the BS softness number.

THERMAL PROPERTIES

Plastic materials are very sensitive to changes in temperature. When the temperature is raised many thermoplastic materials will soften at a comparatively low temperature. If the temperature is lowered then the material may harden at another comparatively high temperature. Thus the temperature range of use of many thermoplastic materials is limited. Such use is limited, not by chemical breakdown, but by hardening or softening. Other problems associated with the use of thermoplastics are the low

thermal conductivity, high specific heat, high coefficient of thermal expansion and a high and non-uniform, shrinkage. The flammability of plastics materials and the smoke produced by their burning, may also be serious disadvantages.

Shrinkage

Shrinkage is the reduction in volume that occurs when a material is cooled from its processing temperature (often quoted shrinkage values are based on injection molded components). Shrinkage is much greater for a semicrystalline thermoplastic material, such as high-density polyethylene (HDPE), than it is for an amorphous, thermoplastic material, such as polystyrene (PS). For PS it is about 0.6% whereas for HDPE it may reach 4%. Shrinkage may also be different from one grade of material to another and will be influenced by changing the processing conditions. It may also be significantly different in different directions (anisotropy), across the flow and along the flow. Because of this it is usual to quote a shrinkage range for each plastic material and the values quoted (Table 5.) should only be taken as a guide. Mold shrinkage is defined as the change in dimensions between the size of the cavity and the molded part 24 hours after the part is ejected from the mold. Mold shrinkage is quoted as a percentage, for example, 0.4%, or as a linear shrinkage, such as 0.004 in/in or 0.004 mm/mm. A widely used test for the measurement of mold shrinkage is ASTM D 955-51. For injection molded specimens, an end-gated bar of thickness 3.2 mm is usually used. The cavity length, both parallel and perpendicular to the flow direction are measured to the nearest 0.02-mm at 23 ±2˚C. At least three test specimens are then molded. After molding the specimens are allowed to cool to room temperature. This cooling time (before initial mold shrinkage is measured) is 1 to 2 hours when the thickness is 3.2 mm. The length (both along and transverse to flow) are measured and then the specimens are returned to storage in a standard laboratory atmosphere (typical conditions are 23˚C at 50% RH). Measurements are made again at 24 hours and 48 hours after molding in order to obtain 24 hour shrinkage and the 48 hour (or normal mold) shrinkage. Results are usually given as mm/mm (same as in./in.) and this is obtained by subtracting the dimension of the sample from the corresponding dimension of the cavity and then dividing by the latter. The mold shrinkage (MS) is given as a percentage if the following formula is used:

MS = [(L0 - L1) / (L0)] x 100. (Eqn. 14)
where L0 is the length in mm of the cavity L1 is the length in mm of the molding
(to the nearest 0.02 mm).

Table 5.
Shrinkage (Mold Shrinkage) Values for Some Thermoplastic Materials

Abbrev.	Material	Linear MS (in/in or mm/mm)	% MS
ABS	Acrylonitrile-butadiene-styrene	0.004-0.007	0.4-0.7
CA	Cellulose acetate	0.003-0.007	0.3-0.7
CAB	Cellulose acetate butyrate	0.002-0.005	0.2-0.5
EVA	Ethylene vinyl acetate	0.007-0.020	0.7-2.0
FEP	Fluorinated ethylene propylene	0.030-0.060	3.0-6.0
HDPE	Polyethylene (high density)	0.015-0.040	1.5-4.0
HIPS	Polystyrene (toughened)	0.002-0.008	0.2-0.8
LDPE	Polyethylene (low density)	0.0165-0.040	1.65-4.0
PA 6	Nylon 6	0.010-0.015	1.0-1.5
PA 66	Nylon 66	0.010-0.020	1.0-2.0
PBT	Polybutylene terephthalate	0.015-0.020	1.5-2.0
PC	Polycarbonate	0.006-0.008	0.6-0.8
POM	Acetal	0.018-0.025	1.8-2.5
PMMA	Acrylic	0.002-0.010	0.2-1.0
PPO	Polyphenylene oxide (modified)	0.005-0.007	0.5-0.7
PP	Polypropylene	0.010-0.030	1.0-3.0
PS	Polystyrene (GP)	0.002-0.008	0.2-0.8
PTFE	Polytetrafluoro-ethylene	0.050-0.100	5.0-10.0
UPVC	Polyvinyl chloride-unplasticized	0.002-0.004	0.2-0.4
PVC	Polyvinyl chloride (plasticized)	0.015-0.050	1.5-5.0
PVF	Polyvinylidene fluoride	0.020-0.030	2.0-3.0
SAN	Styrene-acrylonitrile	0.002-0.006	0.2-0.6
Thermoplastic Elastomers			
PP/EP(D)M	Rubber reinforced polypropylene	0.010-0.020	1.0-2.0
SBS	Styrene-butadiene-styrene	0.004-0.010	0.4-1.0
PEEL	Thermoplastic polyether ester	0.004-0.016	0.4-1.6
TPU T	hermoplastic polyurethane	0.005-0.020	0.5-2.0

Specific Heat Capacity

Also known as specific heat and sometimes abbreviated to c or to, sp ht or Cp (when measured at constant pressure). Heat capacity divided by mass (heat capacity is the amount of heat energy required to change the temperature of a body, or of a substance, by 1˚C (or 1K). The amount of heat which must be added to unit mass of a material in order to raise its temperature by one degree. Values are commonly expressed in J/kgK, Btu/lb˚F or in cal/g˚C. To convert from Btu/lb˚F or cal/g˚C to J/kgK multiply by 4186.80. As specific heat varies with temperature, it is necessary to specify the temperature employed when quoting a specific heat value. With a crystalline polymer the heat of fusion causes a large increase in the specific heat value at the crystalline melting point. Beyond that temperature the value falls again. Table 6 gives average values for some materials. The high specific heats and heat contents of plastic materials should be noted together with the difference between amorphous and crystalline materials. The specific heat of filled systems, such as rubber compounds, is a cumulative property of all the compounding ingredients. Heat content is the amount of heat energy that a system contains. Specific heat is commonly measured by determining the heat content (enthalpy) over a temperature range (such as upper processing temperature to room temperature) by methods such as differential scanning calorimetry (DSC) method. If such an average specific beat is known, then the amount of heat that must be removed, for example, by the mold cooling system in injection molding can be estimated as:

Heat Content = mass x specific heat x (melt temp - mold temp) (Eqn. 15)

As the DSC method can take account of the latent heat of fusion at the crystalline melting point, no allowance need be made for it. However, if enthalpy data are available it is best to use them directly. If the information is used for injection mold cooling calculations, assume that only half the heat needs to be removed from components. This is because the cool surface layers of the molding provide sufficient rigidity so that ejection can occur even though the temperature of the inside of the molding may still be very high.

Table 6.
Average Specific Heat and Heat Content for Some Thermoplastic Materials

Material Abb.	Melt Temp (˚C)	Mold Temp (˚C)	Temp. Difference (˚C)	Specific Heat $(Jkg^{-1}K^{-1})$	Heat to be Removed (Jg^{-1})
FEP	350	220	150	1600	240
POM	205	90	115	3000	345
SAN	240	60	180	1968	354
PC	300	90	210	1750	368
ABS	240	60	180	2050	369
PMMA	260	60	200	1900	380
PPS	320	135	185	2080	385

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PS	220	20	200	1970	394
ASA/AAS	260	60	200	2010	402
HIPS	240	20	220	1970	433
PPO	280	80	200	2120	434
PA 6	250	80	170	3060	520
LDPE	210	30	180	3180	572
PA 66	280	80	200	3075	615
PP	260	20	240	2790	670
HDPE	240	20	220	3640	801

Glass Transition Temperature

The glass transition temperature, also known as Tg or the glass-rubber transition temperature is the temperature at which a polymer becomes glass-like on cooling or rubber-like on heating. It is not defined by a sharp, precisely located point, but by a temperature range (Tables 7. and 8.). At the Tg there is a volume increase in polymeric materials on heating. This arises from segmental movements of the molecular chains. The tem perature at which this change in volumes occurs may be measured by dilatometry and used as a measure of glass transition temperature (Tg). Enthalpy changes are also used to determine Tg as are modulus, refractive index, and thermal conductivity changes. Each method may give a different answer and such differences help account for the differences found in the literature between reported glass transition temperatures (Tg) which may be as high as 30˚C.

Melting Point

The melting point, also known as the melting temperature (strictly speaking this is the temperature at the melting point) is the temperature at which a solid material becomes a liquid on heating. It is the temperature at which the solid and liquid phases of a material are in equilibrium at a specified pressure (usually atmospheric). Unlike low molecular weight materials, polymers do not normally have a sharp melting point. Even a semi-crystalline, thermoplastics have broad melting points of as much as 20˚C. An amorphous thermoplastics does not exhibit a melting point, but on heating, but will soften, as the temperature increases, until it becomes a high viscosity melt. True melting is a first order transition and the melting temperature given the symbol Tm. A melting point approximation may be obtained by heating small pieces of the material on a hot plate and noting the temperature at which the material melts. For a more accurate determination, a capillary tube method may be used. The capillary tube method (see, for example, ASTM D 2117) may be used to obtain an accurate measurement of the melting point of a crystalline polymer such as a polyamide (PA). A thin strip of PA is placed inside a capillary tube. The tube is then slowly heated inside a heating apparatus to the temperature where the sharp edges of the specimen become rounded. Reported results have been obtained in different ways, for example, when the last traces of material become a melt. This gives a relatively high Tm and helps account for the differences found in the literature between reported melting points **(Table 7.).**

Table 7.
Glass Transition Temperatures (Tg) and Melting Temperatures (Tm) of Some Thermoplastic Materials

Abbreviation	Material Name	Tg (˚C)	Tm (˚C)
ABS	acrylonitrile-butadiene-styrene	-20/105	
AS	acrylonitrile-styrene - see SAN		
CTA	cellulose triacetate	105	306
CTB	cellulose tributyrate	183	
CAP	cellulose tripropionate		234
FEP	fluorinated ethylene-propylene		271
HIPS	high impact polystyrene	100	
IPS I	sotactic polystyrene	100	240
IPMMA	isotactic polymethyl methacrylate	45	160
PA 6	nylon 6	50	215
PA 11	nylon 11		185
PA 12	nylon 12		175
PA 46	nylon 46		295
PA 66	nylon 66	55	265
PA 610	nylon 610	40	227
PAA 6	polyaryl amie/an aromatic nylon	90	236
PAN	polyacrylonitrile	80/104 D	
PAR	polyarylate	180	
PB	polybutene-1	-25	126
PBAK	polybutyl acrylate	40	195
PBT	polybutylene terephthalate	30	225
PC	polycarbonate	150	225
PCTFE	polychlorotrifluorethylene	49	220
PEHD	high density polyethylene		130
PELD	low density polyethylene	-20	120
PELLD	linear low density polyethylene		127
PEEK	polyetheretherketone		334
PEI	polyether imide	215	
PEK	polyetherketone	154	367
PEOX	polyethylene oxide	-56	66
PET	polyethylene terephthalate	69	260
PMMA	polymethyl methacrylate	99	
PMP	poly-4-methylpentene-1	55	250
PMS	poly-α-methylstyrene	120	

Abbreviation	Material Name	Tg (˚C)	Tm (˚C)
POMCO	polyoxymethylene/acetal copolymer		165
POMH	polyoxymethylene/acetal homopolymer	-13	175
PP	polypropylene	0	165
PPE	polyphenylene ether	210	
PPOX	polypropylene oxide	-62	75
PPS	polyphenylene sulfide	85	282
PS	polystyrene	100	
PSU	polysulfone	190/230	
PTFE	polytetrafluoroethylene	126	327
PVAC	polyvinyl acetate	30	
PVAL	polyvinyl alcohol	50/70	D
PVC	polyvinyl chloride	87	212
PVDC	polyvinylidene chloride	-25	190
PVDF	polyvinylidene fluoride		177
PVF	polyvinyl fluoride	-20	200
SAN	styrene-acrylonitrile	105	
SP	saturated polyester - see PBT and PET		
SPMMA	syndiotactic polymethyl methacrylate	110	>200

(D = decomposes before melting)

Softening Point

The softening point is the temperature at which thermoplastic material softens by a specified amount in a softening point test. The amount of softening is usually measured by the indentation of a weight-load-ed needle (a Vicat Softening Point apparatus will provide this information) or by the bending of a weight-loaded bar as the temperature is slowly increased. A softening point test is a thermal yield test.

Cantilever SP Test

A common softening point test for thermoplastic materials is a cantilever or bending test. Such a test uses a rectangular strip, or bar, which is 31.8 mm/1.25” by 6.35 mm/0.25” by 1.52 mm/0.06”. A 1.5 mm/0.062” diameter hole is located centrally 1.57 mm/0.25” from one end. A 20 g weight is attached to the bar by a piece of cotton thread (which passes through the hole). The end of the strip opposite the hole is held in a clamp, so that 25.4 mm/1” of the strip is protruding. The 20 g weight is attached to the free end. Initially the weight is supported so that there is no load on the test piece. The clamp assembly is then immersed in a liquid heating bath that is approximately 30˚C below the expected SP and the support removed from the weight. While stirring, the temperature of the bath is raised at 1˚C/minute

and the temperature noted when the upper edge of the free (weighted) end coincides with a 30˚ graduation on the clamp assembly. The mean of two tests is taken as the softening point. When the clamp assembly is immersed in the liquid heating bath, the liquid must not affect the properties of the material being tested. Liquids used include liquid paraffin for cellulose acetate (CA) and glycerol for polystyrene (PS), high impact polystyrene (HIPS) and unplasticized polyvinyl chloride (UPVC).

Vicat Softening Point

This is a softening point test that is performed using a Vicat Softening Point needle instrument. This term is sometimes abbreviated to VSP. The result, the Vicat Softening Temperature (VST), is usually quoted in ˚C or ˚F. It is measured by applying a standard load (10 N or 50 N), via a circular indenter (a round flat-ended needle of 1 mm2) onto a plastics specimen. The test assembly is heated at a constant rate of either 50˚C/122˚F or 120˚C/248˚F per hour. The result is reported as 100˚C (10 N, 50˚C). This means that the indenter penetrated into the thermoplastic sample at 100˚C/212˚F for the set distance (for example, 1 mm) while carrying a load of 10 Newtons and at a heating rate of 50˚C. ISO method 306 describes two methods: Method A which uses a load of 10 N, and Method B which uses a load of 50 N. As two heating rates are allowed (50˚C/hr and 120˚C/hr) this means that the results may be reported as:
• Vicat A50 = load 10 N and heating rate 50˚C/hr
• Vicat A120 = load 10 N and heating rate 120˚C/hr
• Vicat B50 = load 50 N and heating rate 50˚C/hr
• Vicat B120 = load 50 N and heating rate 120˚C/hr

Table 8.
Typical Thermal Properties of Some Thermoplastic Materials (˚C)

Material	Tg	Tm	SP	HDT (0.45 Mpa)	(1.8 Mpa)	VSP
ABS	105	-	94	96	84	95
HIPS	100	-	84	85	72	86
PA 66	55	265	180	183	75	185
PE-HD		130	115	75	45	125
PE-LD	-20	120		45		85
PMMA	99		95	97	80	90
POM-H	-13	175	170	120	165	175
PP	0	165	145	140	60	150
PS	100	-	92	97	90	98

Tg = glass transition temperatures, SP = cantilever softening point test,
Tm = melting temperature
SP = cantilever softening point test, VSP = Vicat softening point test,
HDT = heat distortion temperature

Heat Distortion Temperature

The heat distortion temperature is also called the heat deflection temperature. However, it should more accurately be called heat deflection under flexural load or, the heat deflection under load (HDUL). It is often abbreviated to HDT (which may stand for heat distortion temperature or heat deflection temperature). In test specifications, HDT is called deflection temperature under flexural load. Two different flexural loads are generally quoted: 1.8 MPa or 0.48 MPa (264 or 66 psi). In the HDT Test a plastic bar (for example, 110 x 10 x 4 mm which is 4.4 x 0.4 x 0.16") is subjected to three-point bending, by a load that produces a maximum stress of either 1.8 MPa or 0.48 MPa (264 or 66 psi), at its mid-point, while being heated. If the breadth (b) is 4 mm, the depth (d) is 10 mm and the stress required is 1.8 MPa then, the load (F) in Newtons which has to be applied to the mid-point (if the span (L) is 100 mm) is equal to $2Pbd^2/3L$. That is, 2 x 1.8 x 100/ 3 x 100 which equals 4.8 N. This load is applied and the temperature raised at 120˚C per hour. When the bar deflects by 0.32 mm (0.012") that temperature, in ˚C or ˚F is recorded and called the HDT. A comparison of some HDT temperatures for thermoplastic materials is given in Table 9.

Cold Flex Temperature

This is the temperature measured in a Cold Flex Temperature Test. This cold flex temperature test is a brittleness temperature test used to assess the low temperature properties of plasticizers or of plasticized compounds such as plasticized polyvinyl chloride (PPVC). A rectangular strip of plasticized PVC (64 x 6.4 x 1.27 mm thick) is cooled in a bath of methanol and solid carbon dioxide. The temperature is raised at a rate of 20˚C/minute and the strip is twisted using a specified torque: initially the strip is twisted by more than 400˚. A graph is plotted of temperature against time and the temperature for a deflection of 200˚ is read off the graph and called the cold flex temperature.

Table 9.
Comparison of Softening Temperatures for Some Thermoplastic Materials

Material	Abbreviation	HDT (˚C) (1.8 Mpa)	(0.48 Mpa)	VST (˚C) (10N 50˚C/hr)
Polymethyl methacrylate	PMMA	71-99	77-110	114
Polypropylene	PP	50-60	107-120	134
Unplasticized polyvinyl chloride	UPVC	60-77	60-82	85
Acetal	POM	85-120	154-166	160-185
Nylon 66	PA 66	74	245	240
Polycarbonate	PC	132	138	155

Stress Relaxation

The stress relaxation (sometimes called reversion) is the shrinkage, or change in shape, that occurs when a thermoplastic material is heated to a specified, elevated temperature, generally a temperature above the glass transition temperature (Tg). This change of shape is caused by release of molecular orientation, or stress, introduced by alignment of the polymer molecules in the direction of flow. A measure of stress relation may be obtained in the following manner: A component is placed on a piece of paper and an image of the part is traced. The image is then cut out and weighed. The component is heated at the specified temperature for a fixed time. The distorted component is then removed, cooled and placed on another piece of paper similar to the first. The outline of the distorted component is marked and the shape cut out and weighed. A measure of stress relaxation is obtained by comparing the two weights. If the product is a plastic sheet then marking a circle on the sheet and measuring the change in length of two diameters at right angles to each other is used to assess stress relaxation. Usually the two dimensions are the machine direction and the transverse direction.

FLAMMABILITY TESTING

The ability of a plastic material to withstand heat and flame without burning is critical to how it may be used. The requirements placed on appliances, house furnishings, electrical parts and clothing will be much stricter than those for packaging or outdoor furniture. Thus flammability testing is required to assure the suitability of a plastic material for many applications. The flammability testing of plastics is complicated by many factors that may affect the results. The thickness of the sample, location of the flame, orientation of the test specimen, the oxygen concentration, the ambient temperature and air velocity may all have an influence on the results. Two methods for evaluating the flammability are generally used, the Limiting Oxygen Index (LOI) and the Underwriter 's Laboratory rating system (UL94). Some flammability testing results are shown in Table 9.

Limiting Oxygen Index (LOI)

The LOI Test is one of the few, reproducible, flammability tests that produces quantitative results. It measures the amount of oxygen required for a material to support combustion. In this test the sample is ignited in a chamber containing a controlled nitrogen/oxygen atmosphere in which it will burn. The toxygen level is then reduced until the sample is extinguished. The LOI is the lowest percent oxygen that will support combustion of the sample. Thus this test can be used to test the performance of plastic materials that will not normally burn in air. In general, any material with an index greater than 28 (air contains 21% oxygen) is considered flame resistant.

Table 10.
Typical Limiting Oxygen Index (LOI) Results

Material	Abbreviation	Oxygen Index (%)
Acrylonitrile-butadiene-styrene	ABS	19-35
Acetal	POM	15-16
Nylon 6	PA 6	21-24
Nylon 66	PA 6	21-30
Nylon 11	PA 11	25-32
Phenol-formaldehyde	PF	35
Polyarylate	PAR	34
Polycarbonate	PC	26
Polybutylene terephthalate	PBT	18
Polyether ether ketone	PEEK	35
Polyether sulphone	PES	34
Polyethylene	PE	17
Polyethylene oxide	PEO	15
Polyethylene terephthalate 30%GF	PET 30%GF	31
Polyimide	PI	32
Polymethyl methacrylate	PMMA	17
Polyphenylene oxide (modified)	PPO	28
Polypropylene	PP	17
Polystyrene	PS	18
Polysulphone	PSU	30
Polyvinyl chloride	PVC	23-43
Polyvinyl alcohol	EVOH	22
Polyvinylidene chloride	PVDC	60
Polyvinylidene fluoride	PVDF	44
Polytetrafluoroethylene	PTFE	95

UL94 Flame Class Rating

The Underwriter's Laboratory has established a series of qualitative ratings of flame retardance, listed in their UL94 Bulletin, that are broadly accepted in the plastics industry. In the tests, variables such as the flame size as well as the sample form, preparation and orientation are strictly controlled. The ratings generated include:

HB - Horizontal burn (inches/min.)
V-0 - Vertical burn, average burn of 5 sec. or less
V-1 - Vertical burn, average burn of less than 25 sec. (no burning drops)
V-2 - Vertical burn, average burn of less than 25 sec. (burning drops)

5V - More severe than V-0 (5 inch flame, 5 positions, 5 ignitions,
no burn through, no drips)
Other generally accepted flammability tests include the ASTM D- 635 Horizontal Burn Test, the ASTM
E-84 Tunnel Test, the ASTM E-162 Radiant Panel Test, and the Ohio State Cone Calorimeter Test.

Table 11.
Typical Results from a UL 94 Vertical Burning Test

Material	UL 94 coding
Acetal	HB
ABS	HB
ABS/PVC alloy	V-1
ABS/PC blend	V-0
Nylon 6	V-2
Nylon 66	V-2
Glass reinforced nylon 66	V-0
Glass reinforced PET	V-0
Glass reinforced PPS	V-0
Glass reinforced polycarbonate	V-0
Glass reinforced polysulphone	V-0
Polyarylate	V-0
Polycarbonate	V-2
Polyether ether ketone	V-0
Polyetherimide	V-0
Polyphenylene oxide	HB to V-0
Polyethersulphone	V-0
Polysulphone	V-0

MELT FLOW RATE

The most commonly used test is usually referred to as MFR or MFI. Both terms refer to the same test
and stand for melt flow rate and melt flow index, respectively. This test is popular, particularly for
polyolefins, since the test is easy to do and understand and the instrumentation is inexpensive. A
specified force, produced by an accurate weight, extrudes a heated plastic material through a circular
die of a fixed size, at a specified temperature (Figure 12.). The amount of PE extruded in 10 minutes
is called the MFR and results are reported as, for example, MFR (190, 2.16) = 2.3. This means that the
temperature was 190˚C and a force, producing load of 2.16 kg, was used. Under these conditions, 2.3
g of the plastic material was extruded in 10 minutes. MFR is general a low shear rate test where the
shear rate may be as low as 1 sec-1. Weights larger than 2.16 kg may be used as well as different tem-
peratures. These will depend upon the material and the grade of material being tested (Table 12.). With
UPVC a weight of 20 kg may be employed, while the suggested temperature (in ASTM D 3364) is 175˚C
(347˚F). (See Flow Rate Testing).

Figure 12. Melt Flow Rate Tester

Method A

Method A, also known as Procedure A, is a manual cut-off operation used for materials having flow rates that fall within 0.15 to 50 g/10 minutes. The piston position during the timed measurement, (that is, the position of the piston tip) is required to be between 51 and 20 mm (2.0 and 0.8 in) above the die. The test specimen can be in any form that can be introduced into the heated barrel. The conditions of temperature and load can be selected by consulting the standard. For example, for a PE with an expected MFR of 2, the temperature would be 190˚C and the load would be 2.16 kg. After packing a precisely measured amount of PE (in the range of 3 and 5 g) into the barrel, the sample is allowed to heat for 4 minutes with the piston in contact with the material. Then the weight (2.16 kg) is placed on top of the piston. After a further 3 minutes (usually between 2 and 4 minutes) the lower reference mark on the piston must be level with the top of the barrel. The material is then allowed to freely extrude for a specified time (such as 3 minutes), after which the extrudate is carefully cut off and saved. This should be repeated three times if possible, before the upper reference mark reaches the top of the barrel. The three samples are then individually weighed, to the nearest milligram (0.001g), and the average mass in grams is found. The flow rate is reported as the rate of extrusion in grams in 10 minutes (obtained in this case, by multiplying the average mass of polymer extruded (Mp) by 3.33). Thus

MFR = MFI = Mp (600/t) (Eqn. 16)

where: t = the cut-off interval expressed in seconds (s)
Mp = the mass of polymer extruded

Method B

Method B is also known as Procedure B and is an automatically timed flow rate measurement used for materials having flow rates that fall within 0.50 to 1,200 g/10 minutes. To ensure reproducibility, the timing device must be accurate to within ±0.1 seconds and the position of the piston foot at the end of the test must be 25.4 mm (1 in) above the die. During the measurement, the length of timed piston movement must be measured to within 0.025 mm (0.001 in) over a prescribed distance. This measurement may be achieved by using an opaque flag, hung from the piston, which interferes with the passage of light to an electronic eye. It is more common today, however, to use a mechanical encoder connected to the piston. If the system is computerized, then all the operator has to do is to select the test conditions of temperature and load by consulting the standard or the memory and load the material. The test specimen can be in any form that can be introduced into the barrel. The electronics will automatically control the temperatures and time the measurements (and even change the weight during the test run if required). The apparent melt density of the polymer (see Method A to B Conversion) at the test temperature must be entered to allow the calculation of the weight of extrudate from the piston displacement. Once the test has been performed then the electronics can calculate flow rate, flow rate ratios, viscosity, shear rate and shear stress. The electronics also may contain the statistical equations for SPC/SQC analyses of the data for quality control purposes.

Method A to B Conversion

Conversion from Method A to Method B may be obtained on machines where an appropriate electronic optical eye, mechanical encoder or computerized control system is used. The operator runs the test as if it is a Method A test, while the machine conducts a Method B test. Upon completion of the test the apparent density is obtained using the data from both tests and setting the equations equal and solving for melt density.

By Method A, the melt flow rate (MFR) is MFR = Mp (600/t) Where Mp is the average mass extruded (M) within the cut-off interval t (expressed in seconds).

By Method B,

MFR = πR^2 L DM (600/T) (Eqn. 17)

Where R is the piston radius in cm, L is the effective length of the

flag in cm, A is the apparent melt density in g/cm3 and T is the time taken for the test measurement (in seconds). If the two MFR's are the same then, the equations may be solved for A (Table 5.). The advantage of this system is that by using an apparent density obtained from any given machine, Method B will always equal Method A and it takes into account frictional and other variations for that specific instrument.

Increasing Shear Rate and Stress

Melt Flow Rate (MFR) testing is a low shear rate test (the shear rate may be as low as 1 s-1). Larger weights and/or different temperatures may be used depending on the material and grade of material (Table 12.) to produce higher shear rates or to make the test practical. With un-plasticized polyvinyl

chloride (UPVC) a weight of 20 kg/44.1 lb is often employed at a temperature (ASTM D 3364) of 175˚C/347˚F. When the test is run with such a high load, or with the even higher load of 21.6 kg/47.62 lb, then it may be referred to as "the high load melt index" or the HLMI.

Flow Rate Ratio

Since polymer viscosity varies as a function of shear rate, the single point determination by a melt indexer does not fully characterize material flow. To obtain more useful information, flow rate testing may be done with more than one load. For example, in blow molding the sag behavior of the parison is best measured by the low shear flow, while the flow through the die lips is best measured by the higher shear flow. The Flow Rate Ratio is obtained by dividing the flow rate obtained when a large load is used by the flow rate obtained under a smaller load. The load ratio, which is generally 10:1, may, on some instruments, be measured automatically during a single test run.

Melt Volume Index

An abbreviation used for this term is MVI. MVI is defined as the volume of thermoplastic material extruded through a die during a specified time and is expressed in cm3/10 min (MFI is in g/10 min). It is measured by performing a Method B test and doing the calculation without using the melt density. Specifications for this test can be found in DIN 53735. A rating of MVI (250/5) means that the melt volume index, in cm3/10 min, was measured at 250˚C and under a load of 5 kg.

Table 12.
Suggested Temperatures (˚C) and Loads (Kg) for MFR Tests

Material	Temp. (˚C)	Load (Kg)
Acetal (POM-H & POM-CO)	190	2.16 or 1.05
Acrylic (PMMA)	230	1.2 or 3.8
(a) Acrylonitrile butadiene styrene (ABS)	200	5.0
(b) Acrylonitrile butadiene styrene (ABS)	230	3.8.
(a) Cellulose esters	190	0.325, 2.16 or 21.6
(b) Cellulosic esters (CA, CAB CP)	210	2.16
Nylon 66 (PA 66)	275	0.325
Nylon 6 (PA 6)	235	1.0, 2.16 or 5.0
Polychlorotrifluorethylene (PCTFE)	265	12.5
(a) Polyethylene (PE)	125	0.325 or 2.16
(b) Polyethylene	190	0.325, 2.16, 10 or 21.6
(c) Polyethylene	310	12.5
Polycarbonate (PC)	300	1.2
Polypropylene (PP)	230	2.16

(a) Polystyrene (PS or HIPS)	190	5.0
(b) Polystyrene	200	
(c) Polystyrene	230	1.2 or 3.8
Thermoplastic polyester (PBT or PET)		
(a) Polyterephthalate	210	2.16
(b) Polyterephthalate	250	2.16
(c) Polyterephthalate	285	2.16
Polyphenylenesulfide (PPS)	315	5.0
Unplasticized PVC (UPVC)	175	21.6

MELT VISCOSITY

This is the viscosity of a polymeric material in its melted form. An abbreviation used for this term is MV. Viscosity is resistance to flow or internal friction. The term viscosity is sometimes used as an alternative way of saying coefficient of viscosity or dynamic viscosity.

Ease of Flow

Plastic materials differ widely in their viscosity, or ease of flow. The problem of testing such materials is made more difficult by the fact that each material is available in a range of grades, each of which also may have a different flow behavior. The situation is made even more complicated by the fact that the flow properties of plastics are non-Newtonian. In most cases, plastics are pseudo-plastic materials. This means that they become less viscous (easier flowing) when they are moved faster. Therefore, there is not a linear relationship between pressure and flow. This means that the flow properties cannot be represented meaningfully by one number. Thus flow testing over a range of conditions is required.

Viscosity Units

Shear stress is usually designated by the Greek letter τ and has the units of force per unit area.
1 dyn cm2 = 0.002088 lbf ft2 = 0.0000145 lbf in2 or psi.

Shear rate is usually designated by the Greek letter gamma ($\dot{\gamma}$) with a dot above the letter, that is, gamma dot or g. No matter what system of units is used, 1/time (in seconds) represents the units of shear rate. That is, reciprocal seconds or sec-1.

Viscosity (η_a) at a particular shear rate is obtained by dividing τ (the shear stress) by the corresponding $\dot{\gamma}$ (the shear rate). This is an apparent viscosity. In practice the word 'apparent' is often omitted. Apparent viscosity has the units of force per unit area times time (in seconds).

One poise = 1P = 10-1 Pa-s = 10-1 Ns/m2 = 0.000 014 5 lbf s in2
One poise = 1P = 0.1 Pa-s = 0.1 Ns/m2
1 Pa-s = 1 Ns/m2 = 0.102 kgf s/m2 = 10 P = 0.02088 lbf s ft2 = 0.000145 lbf s/in2

Capillary Rheometer Studies

Viscosity values are obtained by dividing the shear stress required for polymer flow by the shear rate of that flow. Both these values may be obtained from capillary rheometer studies. A capillary rheometer is a test instrument used to study the rheological properties of polymer melts by forcing the melt through a capillary (fine) die using a piston, driven at a known speed, at a constant material temperature. The pressure opposing constant flow or the force needed to maintain the specified flow rate is measured. The piston speed is then changed and the new force/pressure (needed to maintain this speed) is measured and recorded. This procedure may be repeated at different barrel temperatures. Knowing the barrel dimensions and the ram speed, the volumetric flow rate through the die can be calculated. In turn, the shear stress and the shear rate may then be calculated and used to construct flow curves. Therefore, characterization of a material's shear flow properties may be done, over a range of temperatures and imposed rates, (Table 13.) using the laboratory capillary rheometer (LCR). (See Flow Properties Assessment in Section 2)

The shear stress and shear rate conditions used for a test may closely approximate those used in a production process, so that the measured flow properties are representative of those seen at different points in the production process.

Extrusion Testing

Checks may be made on incoming raw materials and thermoplastics by using a small, single-screw extruder as a rheometer. For example, a rod die may be specified and the machine set at specified temperature. The extrusion behavior is measured over a range of screw speeds and graphs are plotted of output against screw speed. Graphs of temperature against screw speed or die swell against screw speed can yield valuable data. In this way, the flow behavior of a particular material is characterized over a series of melt temperatures. One of the major problems is maintaining the set temperature, as any alteration in screw speed quickly alters the extrusion cylinder temperatures and then the melt temperature, as a result of shear heating. For this reason the extruder should be fitted with an efficient cooling system which can remove excess heat from the barrel.

TABLE 13.
Suggested Temperatures for High Shear Rate Rheometry

Polymer (Abbreviation)	Test Temperature (˚C/˚F)	Range (˚C/˚F)
ABS	240/464	230-270/446-518
ASA	260/500	250-280/482-536
BDS	220/428	190-230/374-446
EVA	180/356	140-225/284-437
FEP	350/662	300-380/572-716
HDPE	240/464	205-280/401-536
HIPS	240/464	200-270/392-518

LDPE	210/410	180-280/350-536
LLDPE	210/410	160-280/350-536
PA	See PA 6, PA 11, PA 12 & PA 66	
PA 6	250/482	230-280/446-536
PA 11	255/491	240-300/464-572
PA 12	255/491	240-300/464/572
PA 66	280/536	260-290/500-554
PBT	250/482	220-260/428/500
PC	300/572	280-320/536-608
PE	See HDPE, LDPE and LLDPE	
PEEK	370/698	360-380/680-716
PEI	380/716	340-425/640-800
PET	275/527	260-300/518-572
PES	360/680	330-380/626-716
PMMA	240/464	210-270/410-518
POM-CO	205/401	190-210/374-410
POM-H	215/419	190-230/374-446
PP	240/464	220-275/428-527
PPE	See PPO	
PPO	280/536	260-300/500-572
PPS	320/608	290-360/554-680
PPVC	180/356	175-200/347-392
PS	220/428	200-250/392-482
PSU	360/680	330-380/626-716
PVC	See PPVC and UPVC	
PVDF	225/437	220-250/428-482
SAN	240/464	200-270/392-518
UPVC	195/383	185-205/364-401
RMPP	240/464	220-275/428-527
TPE	See TPE-A, TPE-E, TPE-S, TPE-U and TPE-OXL	
TPE-A	200/392	185-240/364-464
TPE-E	220/428	195-255/383-491
TPE-S	170/338	150-200/302-394
TPE-U	200/392	180-230/356-446
TPE-OXL	190/374	180-200/356-392

MEASUREMENT OF ELASTIC EFFECTS

The most important elastic effects are die swell, melt fracture, sharkskin, frozen-in orientation and draw down. The conditions necessary to initiate the occurrence of melt fracture and sharkskin can easily be measured on a high shear capillary rheometer. However, melt fracture, sharkskin and draw down are often measured, or studied, on laboratory-sized extrusion equipment and the results correlated with the appropriate production-sized equipment that is running the same grades of material.

Extrusion Testing

A small, single-screw extruder may be used as a rheometer. Such a machine might have a screw size of 19 mm and a length to diameter ratio (L/D) of 20:1. Usually a rod (capillary) die is specified so the shear rate through such a die may be easily calculated. The machine is usually fitted with transducers to measure die pressures and melt temperatures. The machine is set at a specified temperature profile and once the set temperatures have been reached the extrusion behavior is measured over a range of screw speeds. Output, screw speed and melt temperature are all measured and recorded. Samples of the extrudate may be kept and identified for subsequent examination to reveal defects such as sharkskin and melt fracture. The temperatures are then changed and the procedure followed again. Graphs are plotted of output, melt temperature and die swell against screw speed. The shear rates and stresses that cause problems, then can be calculated from the equipment dimensions and the output rate. Such an extruder can also be fitted with different dies and ancillary equipment so that cast film can be produced at the shear rates where production problems occur. However, even the use of a small extruder is expensive (in terms of both capital outlay and running costs) and so, most studies are performed on capillary rheometers (See Flow Property Assessment Section).

Die Swell

Die swell is usually measured on samples of circular cross-section that have been extruded downward from a capillary rheometer fitted with a circular die. Accurate measurement and interpretation of die swell measurements requires care since, the weight of the extrudate may cause drawing down of the extrudate. To ensure that a circular cross-section is obtained from the die, the extrudate must be given time to freeze while suspended, since it can distort if it is allowed to lie on a surface before it has hardened. Drawing down can be avoided by extruding into a bath containing a liquid of the same density as the polymer, which is placed immediately below the die. Draw down minimization may also be done graphically. Measurements of extrudate diameter are made at several points away from the leading end of the extrudate (obtained by cutting the extruded sample at the die outlet). By means of a graph, the theoretical die swell at this leading edge may be found by extrapolation. Somewhat more simply, there is little loss in accuracy if the experimenter always makes measurements at the same distance from the leading edge. The distance chosen should be the point at which the die swell is approximately a maximum. If the extrudate is smooth and circular, then extrudate measurements may be made using a projection microscope. A laser micrometer, however, allows very accurate measurements of both the extrudate and of the die. If the sample is not round and smooth (due to

sharkskin, melt fracture or some other problem) the best procedure is to weigh (M) a known length (L) of the extrudate and from a knowledge of the density (σ) calculate the extrudate diameter (D) by the formula $D^2 = 4M/\sigma \upsilon L$. For amorphous materials, it is satisfactory to use the density of the solid polymer. In the case of crystalline polymers, however, the density will depend on the rates of cooling from the die and for accurate measurement the density should be obtained from the extruded sample.

Anisotropy and Orientation

As the result of the rapid cooling occurring in production processes, such as injection and blow molding, the moldings usually contain molecules which are orientated in the flow direction: this means that there is a "grain effect" present like the one that exists in wood. Because of the grain, the wood is stronger in one direction that it is in another, that is, the products have anisotropic properties. An easy way of quantifying the anisotropy, or orientation, is to cut samples from the product, at two directions at right angles to each other (along the flow and across the flow). Then measure a property which varies significantly with orientation, such as flexural modulus or tensile strength. Impact strength is also affected by such frozen-in orientation. In an Izod impact test, where the sample has been injection molded with the gate at one end of the sample, the molecules will be roughly aligned with the long axis of the sample. Thus to break the sample, in a standard Izod test, would require fracture to occur across the elongated molecules. This will give a higher impact strength than would be recorded with non-oriented samples. On the other hand, if impact strength is being measured by dropping a weight onto a flat plate, lower impact strengths will be recorded with more oriented moldings. This is because fracture can occur more easily parallel to the direction of orientation and allows fracture to occur between, rather than across, molecules. Shrinkage caused by oven heating is also used to assess the amount of stress relaxation that will occur on heating a plastic molding or extrusion product. Such a test is used as a measure of how well the product was produced and/or, if a product will withstand use at elevated temperatures. The greater the orientation the more the component will shrink on heating. The dimensions of the product are checked after oven heating for a specified time and at a specified temperature (See Stress Relaxation in Section 2).

CHEMICAL RESISTANCE
Guidelines

Generally, plastics demonstrate a good resistance to chemical attack. Of course this resistance is dependent on the plastic and the nature of the chemical agent. The reported resistance of a plastic, to attack by a chemical agent, should only be considered as a guideline. There are frequently many grades of the same material and some may display better resistance than others. In general, the chemical resistance of semi-crystalline thermoplastics is superior to that of amorphous resins. With all plastics the chemical resistance is reduced as the temperature is increased.

Environmental Stress Crack Resistance (ESCR)

The short term chemical resistance of most plastics is generally well known. The long term effect of

course this resistance is dependent on the plastic and the nature of the chemical agent. The reported resistance of a plastic, to attack by a chemical agent, should only be considered as a guideline. There are frequently many grades of the same material and some may display better resistance than others. In general, the chemical resistance of semi-crystalline thermoplastics is superior to that of amorphous resins. With all plastics the chemical resistance is reduced as the temperature is increased.

Environmental Stress Crack Resistance (ESCR)

The short term chemical resistance of most plastics is generally well known. The long term effect of exposure to various chemical environments, sometimes referred to as Environmental Stress Crack Resistance (ESCR), however, often shows quite different results. While a plastic may appear resistant to a particular environment, such as water, a long term exposure (~100 hours or more) may show a totally different result. Even if it survives this test it may fail if the sample is under stress. The only way to obtain this information is by doing the test, usually by immersion or direct contact with the chemical agent. Sometimes the samples are stressed on special jigs. The resistance is then reported as the time to first appearance of cracking or degradation and the calculated stress on the part. With metals the attack of a chemical agent is usually confined to the surface and involves corrosion and loss of weight. Plastics, however, may absorb the chemical reagent and display swelling and softening, accompanied by a gain in weight. In extreme cases, this may be followed by a loss in weight as the surface is dissolved, swollen or decomposed and crumbles away.

ELECTRICAL PROPERTIES

Some of the earliest applications for plastics was as electrical insulators. They have excellent insulating properties as well as being easily shaped.

Resistivity

Most plastics are good insulators and have a high resistance to the passage of electrical current. Since the resistivity of the surface and bulk of a plastic may be different they are both quoted. In both cases, the higher he value, the better the insulating qualities. A good conductor, such as gold, has a volume resistivity of 10-6 (Ohm-cm), while carbon is 10-3, conductive plastic ~10+2, cellulose 10=6, PVC 10+14 and polystyrene is 1018. Insulation resistance, a combination of surface resistivity and volume resistivity, is also sometimes quoted. It is the ratio of the direct current voltage applied to the electrodes to the total current between them.

Dielectric Strength

Dielectric strength is a measure of the maximum electrical load a material can withstand before failure. To test dielectric strength, increasing levels of voltage are applied to a sample until fails. It is defined as the voltage per unit of thickness that will cause a catastrophic failure of the insulating material, resulting in the flow of current through the material. It can depend on thickness. For example, the dielectric strength of a 0.001 inch film may be as much as twice that for a 0.005 inch film of the same material

(25.4V/mil = 1 KV/mm). The value decreases rapidly with increasing AC frequency and for some materials the value is decreased by increasing humidity.

Arc Resistance or Tracking

While dielectric strength measures the maximum voltage a material can withstand, and volume resistivity measures it's resistance to the flow of electricity per unit thickness, arc resistance measures a material's resistance to an applied voltage over time. It measures the time, in seconds, that an electrical spark can be applied to a material's surface before it chars. Charring is the cutting of a carbon track across the material's surface, which causes it to become conductive. Plastics that degrade on heating to produce volatiles (gases) show a higher arc (or tracking) resistance than those that do not.

Dielectric Constant

The dielectric constant (also referred to as the permitivity or specific inductive capacity) is a measure of how well a material will store an electrical charge. The lower the value the better the insulating properties. It is the ratio of the storage capacity of a material relative to that of air and has no dimensions.

Power and Dissipation Factors

For most insulators (dielectrics) these two factors are the same and refer to a measure of how much power is converted to heat. This generation of heat is undesirable in an insulator and should be as low as possible. The term loss factor (or dielectric loss index) is the product of the dissipation factor and the dielectric constant. As a result, PVC, which has a high loss factor can be vibration welded, while PE, with a low loss factor, cannot.

Improving Conductivity

For insulation purposes the high resistivity of plastics is an advantage. However, it also has the disadvantage of the capacity for building up a high static charge. This can in turn lead to spark generation or attraction of dust. This can be eliminated by the addition of a conductive filler such as carbon black. The incorporation of lubricants can minimize the generation of static, while the addition of some semi-incompatible liquids can cause static to leak away.

OPTICAL PROPERTIES

Optical properties is a term often used in plastics technology to describe those tests used to characterize the appearance of a film or sheet. The properties commonly measured include refractive index, clarity (usually means seethrough clarity), gloss, haze and light transmittance. The melt and die surface temperatures employed in extrusion may have a significant effect on properties such as surface gloss. In general, the higher the melt and die surface temperatures, the better the surface gloss.

Refractive Index

The refractive index is the ratio of the sine of the angle of incidence (sin α) to the sine of the angle of refraction (sin β), when light is refracted from a vacuum into a medium. (Air is often used in place of a vacuum.) As the refractive index varies with the wavelength of light, the wavelength of light used for the measurement is taken as being that for yellow light (sodium D-line = 589.3 nm) unless otherwise stated. The refractive index may be measured approximately by using a microscope: the opposite faces of a uniformly, thick test piece is determined by focusing on opposite faces alternately and measuring the traverse distance. Refractive index is obtained by dividing the true thickness by the apparent thickness. According to ASTM, the preferred method of measuring the refractive index is by use of an Abbé refractometer. A small test piece is kept in touch with the fixed prism with a suitable liquid: the ASTM procedure suggests suitable liquids. White light and a test temperature of 23˚C are used.

Gloss

Gloss is a measure of the ability of a material to reflect light. It is an optical feature of all materials whether transparent or opaque. When a beam of light strikes a surface, the amount reflected will depend not only on the type of surface finish, and refractive index of the material, but also on the angle of incidence and the angle of viewing of the reflected beam. Because of such variations, many methods of measuring gloss exist, varying mostly in the angle of incidence and reflection used. The primary standard of gloss is usually a highly polished, plane, black glass surface with a refractive index of 1.567. This standard is assigned the value of 100 gloss units for each of the geometries, or arrangements, of the incident and reflected light beams. For example, in ASTM tests, 20˚ and 85˚ (to the vertical) are used. The 20˚ angle is used for high gloss materials and the 85˚ angle is used for low gloss materials. In many instances tests are made on specimens cut from finished products. No further preparation is usually necessary unless test temperature and humidity are known to affect the result (when careful conditioning prior to testing will be needed). Specimens made for comparison by injection and/or compression-molding need to be made very carefully as the result may be affected by many factors. The following are important in injection molding: Mold temperature, the rate of mold filling and mold finish.

Light Transmittance

The transparency of a material is defined in terms of two parameters or measurements. These are its light transmittance and haze. Light transmittance is a ratio obtained by measuring how much light passes through a sample of a material compared to how much light is passed without the material. Light that is not transmitted is reflected, scattered or absorbed. The upper limit for light transmittance achieved by high quality acrylic sheet is about 92%. Light transmittance is measured by placing a flat test specimen in front of, and at right angles to, a collimated (parallel) beam of light. A photocell measures the amount of light passing directly through the material. The specimen is then removed and the amount of light reaching the photocell is measured again. The ratio of the two measurements, expressed as a percentage, is the light transmission.

When the specimen is thin and flexible (thin film rather than rigid sheet) an integrating sphere haze-meter must be used. This consists of a light source and lens which gives a collimated beam that passes through the specimen into an integrating sphere. The inside of the sphere is coated with a highly reflective white powder. The sphere can be moved so that all the light entering it either passes into a light trap, or falls on the wall of the sphere where it is repeatedly reflected until it reaches a photocell. Output from the photocell is displayed on a galvanometer. Light transmittance measurements are made by first setting the instrument so that without a specimen in position, the galvanometer reads zero (that is, all the light passes into the trap) and 100 when the sphere is tilted and all the available light reaches the photocell. Interposition of the specimen causes the galvanometer reading to fall to a value of less than 100, and this figure is the light transmittance percentage.

Haze

Haze is the amount of light scattered in a forward direction, either by surface irregularities and/or non-homogeneities within a translucent or transparent material. The latter can be such things as dust, filler particles, or crystalline regions of different refractive index from the rest of the material. When the percentage of haze is greater than 30% the material is considered to be translucent rather than transparent. It is possible to distinguish between haze due to surface roughness from that due to non-homogeneities by coating a small area of the specimen on both sides with a liquid of the same refractive index as the polymer (for instance, 1.49 for polypropylene). If the transmission in this wetted area improves, then the haze is mainly due to surface imperfections. After a light transmittance measurement, and with the specimen still in position, the integrating sphere haze-meter is set so that all the available light reaches the photocell (See Light Transmittance). The galvanometer reading is increased from its value below 100 to read 100 exactly by using the sensitivity setting of the galvanometer. The sphere is then moved so that all the light except that scattered by the haze passes into the light trap. The scattered light or haze then registers on the photocell, which outputs the value directly on the galvanometer. Haze is the percentage of incident light that is scattered by more than 2.5° from the original, incident beam.

See-Through Clarity

See-through clarity is defined as the ability to see objects, or print, which are in contact with a thermoplastics film. It is a measure of the distortion and/or obscuration of an image when seen through a material. Long distance viewing is often not possible when looking through many plastics films while contact viewing is, however, often possible. See-through clarity may be measured by assessing the optical definition of, for example, Snellen charts at a specified chart-to specimen distance. Such charts consist of sets of parallel lines that differ in line spacing. The charts are viewed with and without the specimen. The narrowest, most closely spaced lines, which can clearly be seen as lines, with and without the specimen in front of the chart is a measure of seethrough clarity. The see-through clarity may also be assessed by judging the definition of a well-illuminated, wire grid when viewed through a

film. The view of the grid is compared with a set of eight photographs that cover the range of clarity usual with the material. The test film is then assigned a number (which corresponds with the photograph number that resembles what is seen). Another way of assessing see through clarity is by small-angle scatter. This assumes that small-angle scatter controls the definition of an object. The small angle test uses a stabilized light source to illuminate a hole which is 2.03 mm (0.08 in.) diameter: another hole of the same diameter is located 1.98 m (78 in.) away. A lens located approximately halfway between the two holes, focuses the light from the first hole (the illuminated hole) onto the second hole. When the film is placed behind the lens, that is, closer to the second hole, only light which is transmitted by the film with a deviation of less than 4 minutes is measured by a photocell located behind the second hole. The photocell reading, expressed as a percentage of the intensity of the incident beam, is called the see-through clarity.

MATERIAL IDENTIFICATION

Complete identification of most polymer compounds is very difficult because of the complexity of the formulations. Often, however, what is required is the separation (or identification) of lots of material whose identity has been lost or an identification of the type of material used to make a molded part. Useful simple tests to identify plastic materials include a preliminary examination, density, melting point and behavior on heating.

Preliminary Examination

The material should be inspected before processing and the color, particle size, particle size consistency and any obvious contamination, noted. If a component is being examined then note size, weight, color and any features, or clues, which indicate how the component was made. By way of illustration, a gate scar would indicate injection molding whereas the presence of flash lines would indicate manufacture by compression molding. Such preliminary examinations may indicate if a material is a thermoplastic material or a thermoset.

Density

The densities of most commercial thermoplastic materials are low as they are usually based on carbon and hydrogen. Density is defined as mass per unit volume and therefore has the units of mass and of volume. When expressed in grams per cubic centimeter (g/cc) it is numerically equal to relative density (specific gravity or SG). Very often the absolute density of a material is not required. What is required is an approximate value so as to assist in material identification. An approximate measure of specific gravity/density may be obtained by observing whether the material sinks or floats in a limited range of liquids, for example, water and saturated magnesium chloride. The former has a density of 1 g/cm3 and the latter has a density of 1.34 g/cm3. Most olefin-based materials will float in water (and therefore also in saturated magnesium chloride). Most unfilled, styrene-based thermoplastics will very slowly sink in water, but will float in the saturated magnesium chloride. Most UPVC materials will quickly sink in water and more slowly in saturated magnesium chloride. This test is most useful when performed in

conjunction with a burning test. If an accurate measurement of density is required, then a flotation or displacement method (See Density and Dimensions Section) can be used.

Melting Point

The simplest way of obtaining an approximate value is by heating a small sample of the material on a metal hot plate while measuring the temperature. A heating rate of approximately 50˚C/hour or 100˚F/hour, should be used. It is useful to have a glass rod so that the sample may be moved, or prodded, during heating. Note the mid-point of the obvious softening range. An amorphous thermoplastic material will not have a sharp melting point, whereas a semicrystalline thermoplastic will usually have a relatively sharp melting point (Table 7.).

Behavior on Heating

Often this test may be combined with the melting point test. A glass rod is used to move the material while it is being heated. If the material does not soften on heating then it is probably a thermoset (some heavily filled engineering thermoplastics behave in the same way). If it does soften then it is probably a thermoplastic. An amorphous thermoplastic will have a much broader softening range (not a melting point), whereas a semi-crystalline thermoplastic material will have a melting point. The way that the material burns and the fumes evolved may also indicate the type of material used.